Measurement of the Quality Factor for the Micro Electromechanical System Cantilever Devices by Using Non-Destructive Test Methodology

by

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Thesis Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners. I understand that my thesis may be made electronically available to the public.

Abstract

Development of the reliability and the performance of Micro Electro Mechanical System (MEMS) devices are the most challenging tasks of scientists and engineers. At the same time, there is a need for advance and more complex testing methods determining functional, performance of the MEMS device and to predict device performance from wafer test. Recent developments in the technologies are giving opportunities to the researchers in developing suitable non-destructive Test (NDT) methodologies for testing and evaluation of the MEMS [1].

Among several challenges regarding the commercialization of MEMS technologies, the focus of the current thesis will be to prove reliability of the MEMS devices, to determine performance criteria such as Q-factor.

With regards to reliability and Q-factor; stiction, noise and squeeze film damping are the important occurrences thereby, this report provides very brief general information about these subjects that is to say detailed examination of these are not the main purpose of this thesis.

MEMS technology is a promising platform for next generation sensors and actuators. Despite a substantial amount of research in the field, there are still many challenges regarding the management of energy dissipation in MEMS which limits their performance and reliability. Especially integrated MEMS devices require NDT methods to dynamically test the MEMS structures.

In the current thesis, MEMS cantilever beams have been used as representative samples. Moreover, information about their performance criteria is provided, and challenges for the next generation of MEMS devices are discussed.

A simple method of logarithmic decrement was applied to calculate the Q- factor of several cantilever beams. Furthermore, the project attempts to show how the contacted

cantilever affects the Q-factor of the MEMS devices. Representative samples have been tested under normal air pressure and vacuum in order to eliminate the effect of squeeze film damping factor.

The beam was then stuck as both line and area contact to substrate due to surface tension caused by increasing the high electrostatic forces. This way, the stuck beams were stressed because of the deformation caused by the stiction. The maximum contacted area obtained in this study was 30-40% of length. The Q-factor of the contacted and free standing MEMS cantilever switches was then experimentally evaluated.

The project demonstrated an experimental set-up that utilizes a scanning laser Doppler vibrometer (LDV) with a novel calculation methodology to measure the Q-factor.

Brief information was provided about the MEMS marketing and application to determine the developmental trend of the MEMS devices. Relatedly, potential future research areas related to the MEMS devices was discussed. Deeper insights on enabling technologies, materials and packaging are beyond the scope of the current thesis.

The goal of this thesis is to demonstrate the measurement of Q-factor of the cantilever MEMS devices using NDT methodology and to apply calculation methods which is developed based on the best fitted envelope function methodology. The novelty of this project is to experimentally demonstrate a dramatic increase in the Q-factor quadruples as contact evolves from line to area contact.

Acknowledgement

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Dedication

To my beloved mother and my late (blessed) father,

To

my kids;

Barış, Begüm, Kadir Başar and Eylül Saime

Glossary

Free Molecular Path

An instrument used to measure waves through interference patterns. Interferometry is the process which two waves are combined so they can be studied for differences in their patterns. The fields of study where interferometry is used are astronomy, physics, optics, and oceanography.

Dopant

Chemical term that engineers use to create current paths for semiconductors and other technologies and used in a process called doping. Doping agents include chromium and other similar substances. These are added to semiconductors or other hardware to produce a charged environment.

Hermeticity Test

The reliability effects of defects in the seal deal mainly with contamination and corrosion mechanisms. In hermetic packages (ceramic or metal) moisture can be locked inside during sealing or can outgas from materials inside. Hermeticity tests are applied to ensure moisture cannot get into ceramic, metal or glass packages which have an internal cavity.

Hydrogen Fluoride Release

Silicon MEMS devices created using a sacrificial silicon oxide layer, which when removed, "releases" the silicon MEMS structure and allows free movement. Silicon oxide is typically etched by HF:
$SiO_2 + 4\ HF \rightarrow SiF_4\ (g) + 2\ H_2O$

Metal Oxide Semiconductor

Metal Oxide Semiconductor is a method of creating transistor and consists of three layers, a metal conductor (insulating mostly oxide of substrate) silicon layer, and a semiconductor silicon layer.

Micro Electro Mechanical Systems

MEMS is the integration of mechanical elements, sensors, actuators, and electronics on a silicon substrate through micro fabrication technology, which studies micro-scale physics and micro fabrication processes for the creation miniature devices. MEMS devices typically range in size between sub-microns to sub-millimeter.

Monte Carlo Methods

Numerical methods that use random numbers to compute quantities of interest. This is normally done by creating a random variable whose expected value is the desired quantity. Then simulates and tabulates the random variable and uses its sample mean and variance to construct probabilistic estimates.

Structural Layer

A layer of material that forms a physical structure on a substrate a structural layer is releasable when a sacrificial layer separates it from the substrate.

Steady State

Steady state is the behavior of a vibrating system after it has had plenty of time to settle into a steady response to a driving force.

State-of-the-art

The term "state of the art" refers to the highest level of general development, as of a device, technique, or scientific field achieved at a particular time.

Abbreviations

MEMS	Micro electromechanical systems
NDT	Non-destructive test methods
NDE	Non-destructive evaluation
IC	Integrated circuit
RF	Radio frequency
COT	Cost of test
CAGR	Compound annual growth rate
OEE	Overall equipment efficiency
RFID	Radio frequency identification
CT	Computed tomography
BFEF	Best fit envelope function
MCM	Multi-chip module
GPS	Global positioning system
INS	Inertial navigation system
RMS	Root mean square roughness
TSV	Through-silicon via
VIA	Vertical interconnects access
MUMPs	Multi-User MEMS Processes
CW	Cold weld
MOS	Metal Oxide Semiconductor
HF	Hydrogen Fluoride
LDV	Laser Doppler Vibrometer
MSV	Microscope Scanning Vibrometer
SFD	Squeezing Film Damping
MIR	Magnetic Resonance Imaging

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List of Symbols

The following notations are used throughout the text; other notations are used at their relevant positions:

ω_i	Resonance frequency of *i* number of modes
ω_n	Natural frequency
ω_d	Frequency at damped vibration
β_i	i number of modes, depends on the boundary conditions
φ	Phase angle of damped oscillation
δ	Logarithmic decrement
ζ	damping ratio
m	Mass
k	spring constant
c	damping coefficient
l	Length of the cantilever
θ_C	Contact angle between liquid and solid in air
g	Thıckness of liquid layer
A_w	Wetted area
F	Force applied to maintain equilibrium
Δp_{la}	Pressure difference at liquid-air interface,
γ_{la}	Surface tension of the liquid –air interface,
r	Radius of curvature of meniscus of liquid
A_h	Hamaker constant (J) $0.4 < A_h < 4 \times 10^{-19}$
E_{vdW}	The Interaction energy per unit area due to van der Waals interaction between two flat surfaces
d	Distance between two parallel surfaces (small separation d<20nm)
ρ	Micro beam material density
σ	axial residual stress in the micro beam
A	Micro beam cross-sectional area
b	Micro beam width
cs	Non-dimensional squeeze film damping coefficient
cv	Non-dimensional viscous damping coefficient
E	Micro beam modulus of elasticity
h	Micro beam thickness
I	Micro beam moment of inertia
U_s	Total energy stored
U_d	Energy lost in a single cycle
λ	Mean free path of molecule inside of the MEMS
K_n	The Knudsen number

Chapter I

1 Introduction

MEMS technology involved various components from different engineering branches especially electrical, electronic mechanical and software engineering. MEMS devices are small integrated systems that combine electrical and mechanical components a well as a mean of fabrication and manufacturing. In the most general form, MEMS consist of mechanical microstructures, micro sensors, micro actuators and microelectronics, all integrated onto the same silicon chip. This is shown schematically in Figure.1.1.

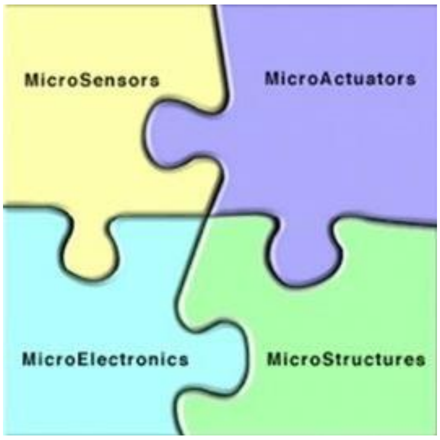

Figure 1.1: *Schematic illustrations of MEMS components* *www.engineersgarage.com/articles/mems-technology)*

MEMS technology can be defined as "miniaturized mechanical and electro-mechanical elements" that are made by micro fabrication technology. The physical dimensions of MEMS devices can vary from below one micrometer to several millimeters. In general MEMS can be grouped based on the lateral dimensional (L) range; surface micro-machined structures which are called classic MEMS (1µm < L< 300 µm), bulk silicon wafer bonded structures (300 μm < L< 3mm) and nano electromechanical systems (NEMS) which overlap with MEMS (10nm < L < 1 μm).

Most important benefits of MEMS devices are their relatively small volume, the reduced cost of materials, and low power consumption. Low power consumption can be achieved because smaller displacements and momentum forces are required.

1.1 MEMS Background

MEMS are the integration of mechanical elements, sensors, actuators, and electronics on a silicon substrate through micro fabrication technology which studies micro-scale physics and micro fabrication processes for the creation miniature devices.

A few years ago it was a nascent technology stressing on the physics and chemistry of the silicon wafer and micro fabrication. Now is the boom time for this field which promises to make assembled systems that able to make cheaper MEMS. Things behave substantially different in micro domain. Forces related to volume, like weight and inertia, tend to decrease in significance. Forces related to the surface area, such as friction and electrostatics tend to be large.

MEMS extend the fabrication techniques developed for the integrated circuit (IC) industry to add mechanical elements such as beams, gears, diaphragms, and springs to devices. Development of the MEMS technology makes the design and fabrication issues first priority for the researchers which motivated the mass production within MEMS fabrication.
The limiting factors of the commercialization of the MEMS are reliability, performance and cost. Reliability, performance and cost of MEMS devices should be considered together with packaging as well. However, these three issues may form a valuable commercial product because the cost of current MEMS packaging is relatively high as much as 90% of total product cost.

1.2 Classification of MEMS and Technology

The MEMS is a process technology used for creation of very small mechanical devices and systems. Microsystem is an intelligent miniaturized system containing sensing, processing and actuating functions integrated onto a single or multi-chip. In the most general form, MEMS consist of mechanical microstructures, microsensors, microactuators and microelectronics, all integrated onto the same silicon chip. This is shown schematically in the Figure 1.2 a and classifications of microsystems technology are shown in Figure 1.2b. :

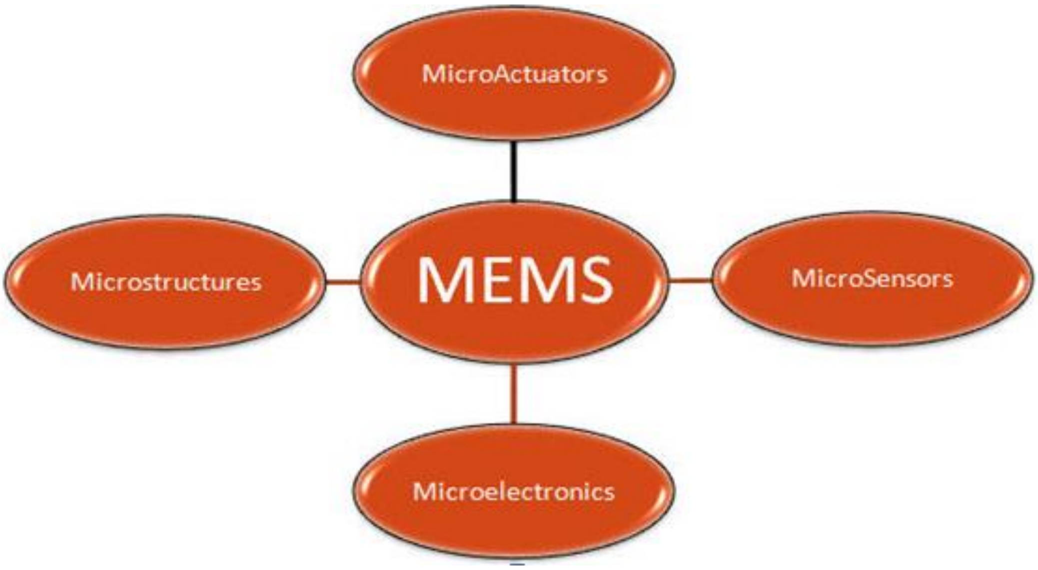

Figure 1.2a: *General form of MEMS*
(*www.engineersgarage.com/articles/mems-technology*)

MEMS components can be classified into six distinct categories. These categories of MEMS are based on their application. These categories include [3]:

- **Sensors** are designed to sense changes in and interact with their environments. Devices found in this class include chemical, motion, inertial, thermal, and optical sensors.

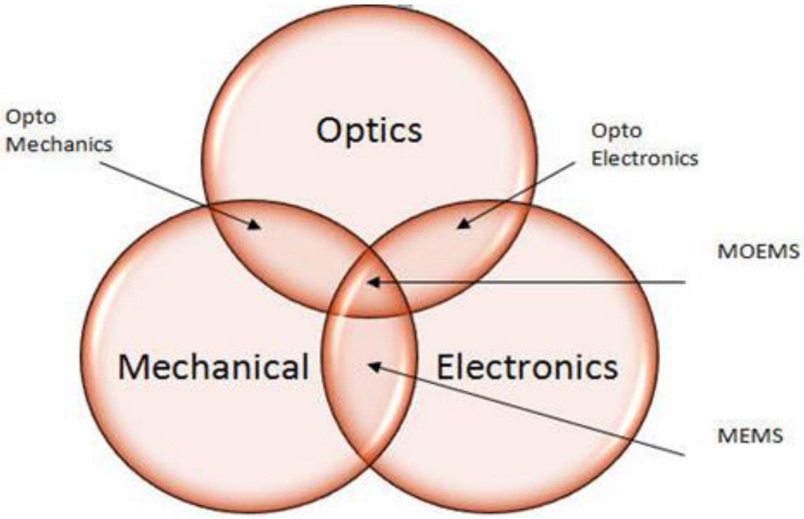

Figure 1.2b: *Classifications of microsystems technology*
(www.engineersgarage.com/articles/mems-technology)

- **Actuators** are devices designed to provide power or excite to other MEMS components. In MEMS, actuators can provide power using either an electrostatic or thermal exciting.
- **Radio Frequency (RF) MEMS** are devices used to switch, transmit, filter, and manipulate RF signals. Typical devices include; metal contact switches, shunt switches, tunable capacitors, antennas, tunable filters, etc.
- **Optical MEMS** are devices designed to direct, reflect, filter, and amplify light. These components include optical switches and reflectors.
- **Micro Fluidic MEMS** are devices designed to interact with fluid-based systems. Devices such as pumps, valves, and channels have been designed and fabricated to transport, eject, and mix small volumes of fluid.
- **Bio MEMS** are devices that, like micro fluidic MEMS, are designed to interact with biological samples. These devices are designed to interact with proteins, biological cells, medical reagents, etc., and can be used for drug delivery or other in-situ medical analysis.

1.3 MEMS Challenges and Future

1.3.1 Industrial Challenges of MEMS

Some of the major challenges facing the MEMS industry include [2]:

- **Foundries**: MEMS companies have limited access to plants and foundries for device prototyping and manufacturing. Affordable, appropriate and easy access to MEMS manufacturing facilities are important challenges to commercialization of MEMS.
- **Design, Simulation and Modelling:** High level of manufacturing experience and knowledge is necessary to design MEMS device. Furthermore, significant time and expense is spent for the development and prototype stage. To increase innovation, creativity, and reduce the cost, there is a need to build up separate design and prototype manufacturing section including modeling simulations and analytical tools.
- **Standardization, Packaging and Testing:** Standardization is an issue for MEMS manufacturing. The opportunity for standardization today is limited, but the potential for more standardization in certain areas is beginning to develop. However, standardization can occur at two levels; packaging and front-end process standardization. Both are underway in the MEMS industry. Additionally, packaging and testing of devices are the greatest challenge facing the MEMS industry. Packaging and NDT methodologies are the most important necessity to overcome the reliability issues of the MEMS. MEMS types of packaging are more complex than most standard IC packages because they require a System-in-Package type of assembly. In terms of reliability of sensor packages are generally

quite bulky and can have very specific constraints like a module with a cavity, a hole in the substrate or metal lead for pressure sensors and microphones, an optical window for optical MEMS, or a full vacuum hermeticity at the die level. As a result, standardization is becoming increasingly critical to support the massive volume grow in unit shipments along with decreasing overall costs associated with MEMS and sensor content, in particular related to their packaging.

- **Education and Training:** The complex nature of MEMS requires educated and well trained scientists/engineers from different backgrounds. The current numbers of qualified specific personnel is lower than the industry demand. Therefore, to meet the projected need lower cost education and methodology is necessary.

1.3.2 Challenges of MEMS Devices

Some of the significant obstacles by the main groups that facing organizations in the development of MEMS devices include [4]: **Assembly and packaging:** MEMS packaging needs to be standardized to support integration. Moreover, the packages which reduce or eliminate mechanical stress and enhance hermeticity are required.

- **Testing:** Testing has to be performed at both levels; the device level and the wafer level. Validation tools are required to predict device performance from wafer tests. A methodology to “Design for Test” has to be developed.
- **Reliability:** More knowledge of the physics of failure is required to develop accelerated life tests. Also, there is a need to share information. Although individual solutions regarding reliability exist, these have to be generalized across the industry.

- **Cost of test (COT)** and overall equipment efficiency (OEE): The issue of COT and OEE continue to be the primary driver for innovation. Traditional COT have been started to be limited by OEE. Tests must be developed as a gate to volume production. As device complexity increases, more complex test methods must be developed.

1.3.3 Future of MEMS

Considering these challenges, this section will present a forecast of the future from the perspectives of technology development [2]. The market for MEMS devices is still being developed but has not reached completely to the level of satisfied market demand. The researchers are focused on surface micromachining today, but in industry the majority of devices are manufactured by using much older bulk methods. Although some surface micro-machined devices are being produced in big volume product, it will take some years for this approach to make a large impact. Despite MEMS being an enabling technology for the development and production of many new industrial needs a completely different set of capabilities and competencies are required to implement it. MEMS involves major scaling, packaging and testing issues, and as a disruptive technology, faces challenges associated with developing manufacturing processes that no longer fit established methods.

For the true commercialisation of MEMS, foundries must overcome the critical technological bottlenecks, the economic feasibility of integrating MEMS-based components, as well as the market uncertainty for such devices and applications. Cost reduction will ultimately result from better availability of the infrastructure, more reliable manufacturing processes and technical information as well as new standards on interfacing

1.3.4 MEMS Markets and Applications

The purpose of this section is to provide brief information on the MEMS market based on the study by Lampo (2012) including applications, future growth opportunities and driving factors for the growth and challenges [42]. The largest markets for MEMS are consumer electronics, automotive, medical, industrial, military and aerospace and telecommunication markets. Development of the MEMS market is shown in Figure 1.3&1.4

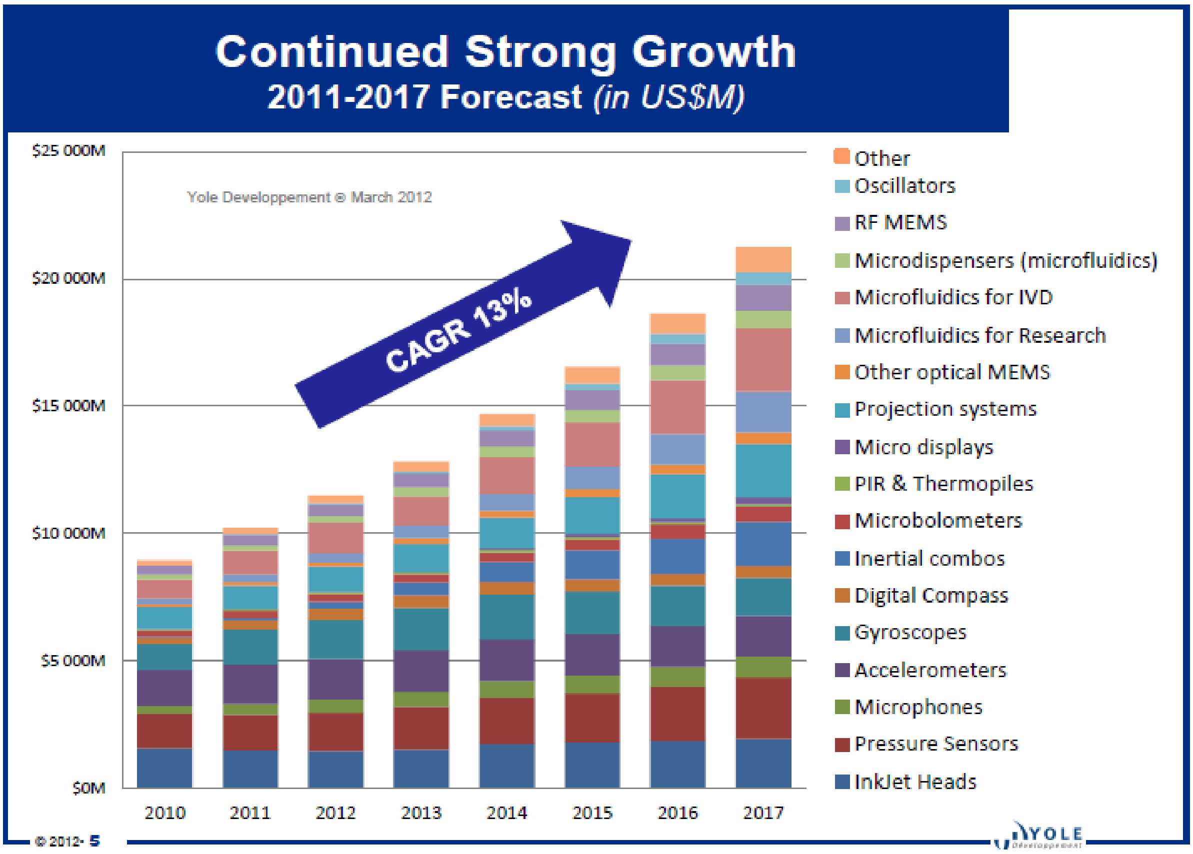

Figure 1.3: *MEMS market forecast ($M) by application 2010-2017 [47]*

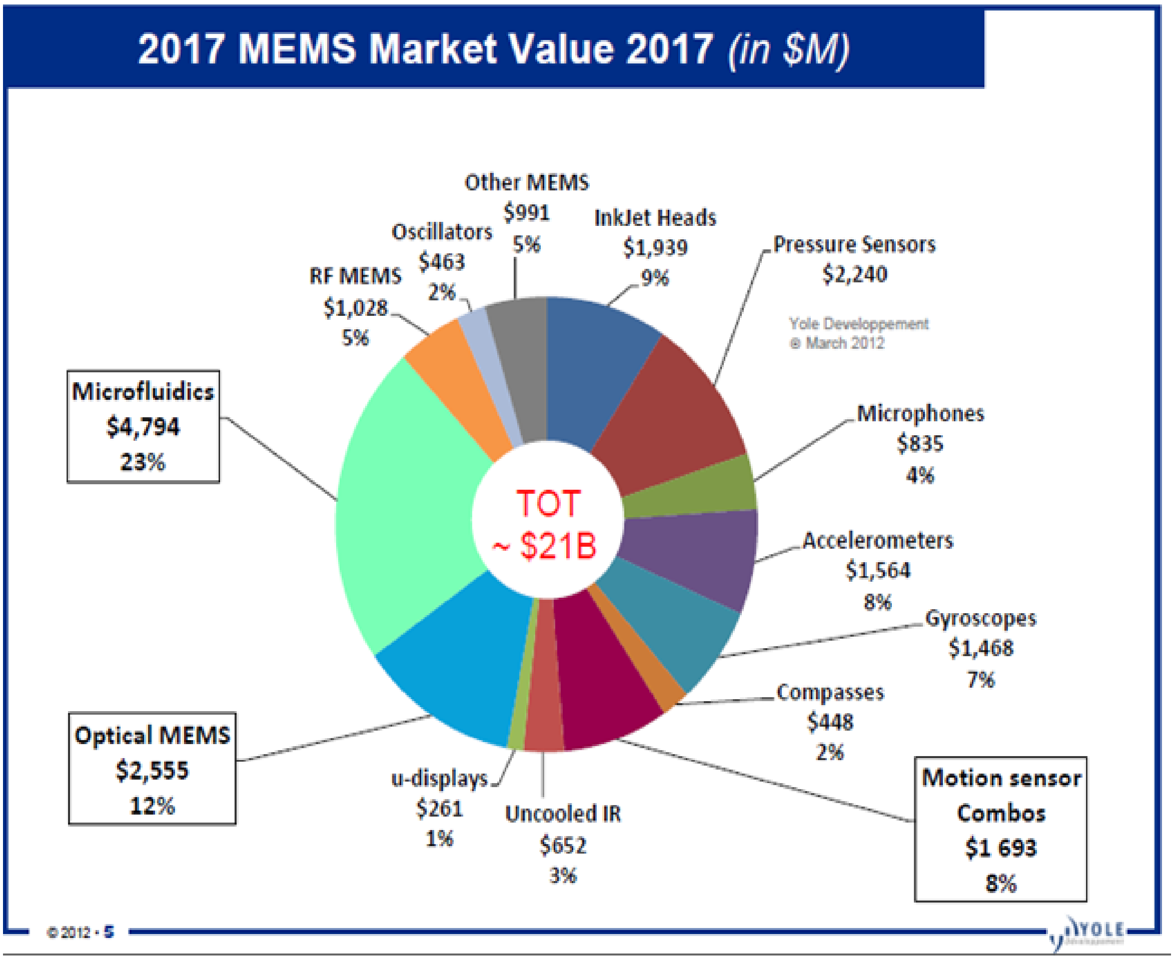

Figure 1.4: *MEMS market value and device share in 2017 [48]*

The key features related to these markets and applications opportunities and driving factors for future growth are summarized in Table 1:

Table 1: The Summary of markets opportunities for future growth

MEMS Market	Largest Application	Growth Opportunities	Driving Factors
Automotive	Safety and Hybrid car	High	Increasing safety regulations, energy costs, passenger comfort
Consumer Electronics	Cell phone, game consoles and Tablets	Very High	New features and applications , small size, light, low power consumption , low cost
Medical	Imaging-diagnostics, therapy-monitoring, mobile applications.	Very High	Personal healthy & therapy, monitoring devices, new and strict regulations
Industrial	Process control and automation, energy harvesting systems	High	Wireless sensing and monitoring, reliability and higher performance requirements
Telecommunication	Optical and wireless communications	Low	Faster data traffic
Military & Aerospace	Pressure monitoring, vision enhancement, missile guidance	Moderate	Navigation systems

1.3.4.1 Automotive Market

Automotive market including Hybrid car applications was the first and dominant growth factor for MEMS devices. A variety of MEMS devices, are used in almost all modern cars, which are shown in Figure 1.5. The automotive market is expected to growth in the following years due to increasing regulations regarding safety, environmental restrictions and demand, passengers comfort and entertainment [45].

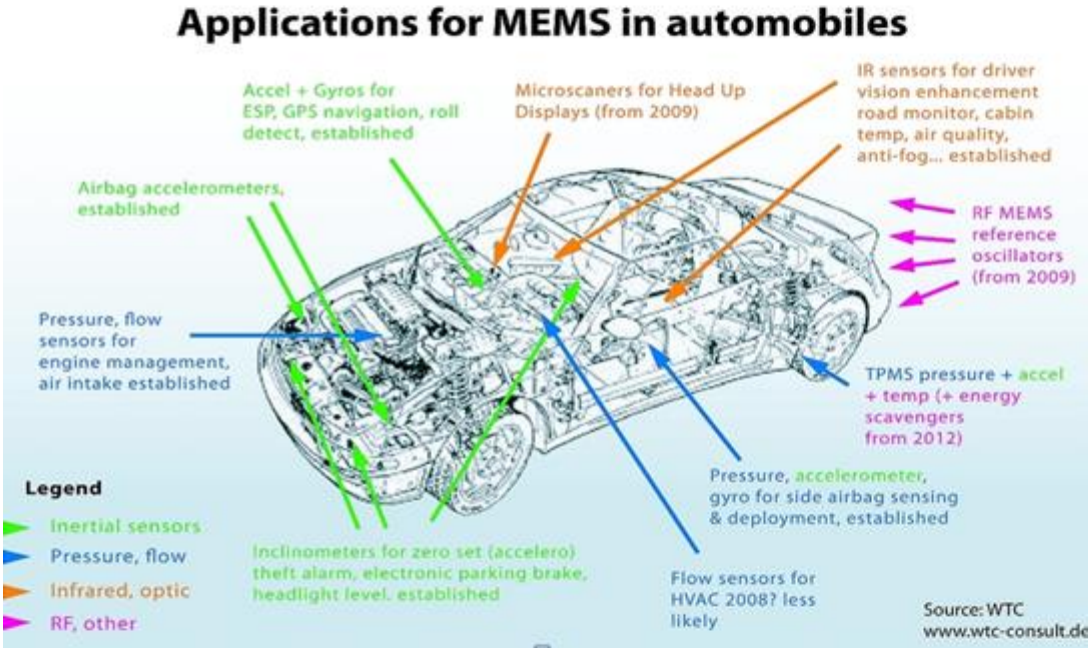

Figure 1.5: *The current and emerging MEMS devices and sensors in automotive applications*

New emerging applications include MEMS devices such as integrated microphones and devices for optical signal handling [48]. Challenges for the MEMS devices are the extreme temperature ranging from -40°C to 85°C for in-vehicle and from -40°C to 125°C for under hood application and the quality and reliability requirements.

1.3.4.2 Consumer Electronics Market

This market is the one of fastest growing MEMS market. Figure 1.6 shows how the changes of global trends effect to the MEMS market.

Among consumer products, cell phones industry is the largest MEMS device user. Other applications for consumer MEMS is game consoles (motions sensors), tablets (integrating variety of different MEMS devices), cameras, projectors, laptops, MP3 players, televisions and Image Sensors markets [47].

The various emerging devices are electronic compasses, RF switches and RF varactors, auto-focus and timing devices motivating the commercial markets in the near future. For example, in Figure 1.7, the current and emerging MEMS devices used in modern cell phones are presented. The new functionalities, smaller size and light in weight, the ability to be integrated in the small portable products, low power consumption of devices and low-cost are main driving factors and also the challenges for the MEMS devices in consumer applications [43].

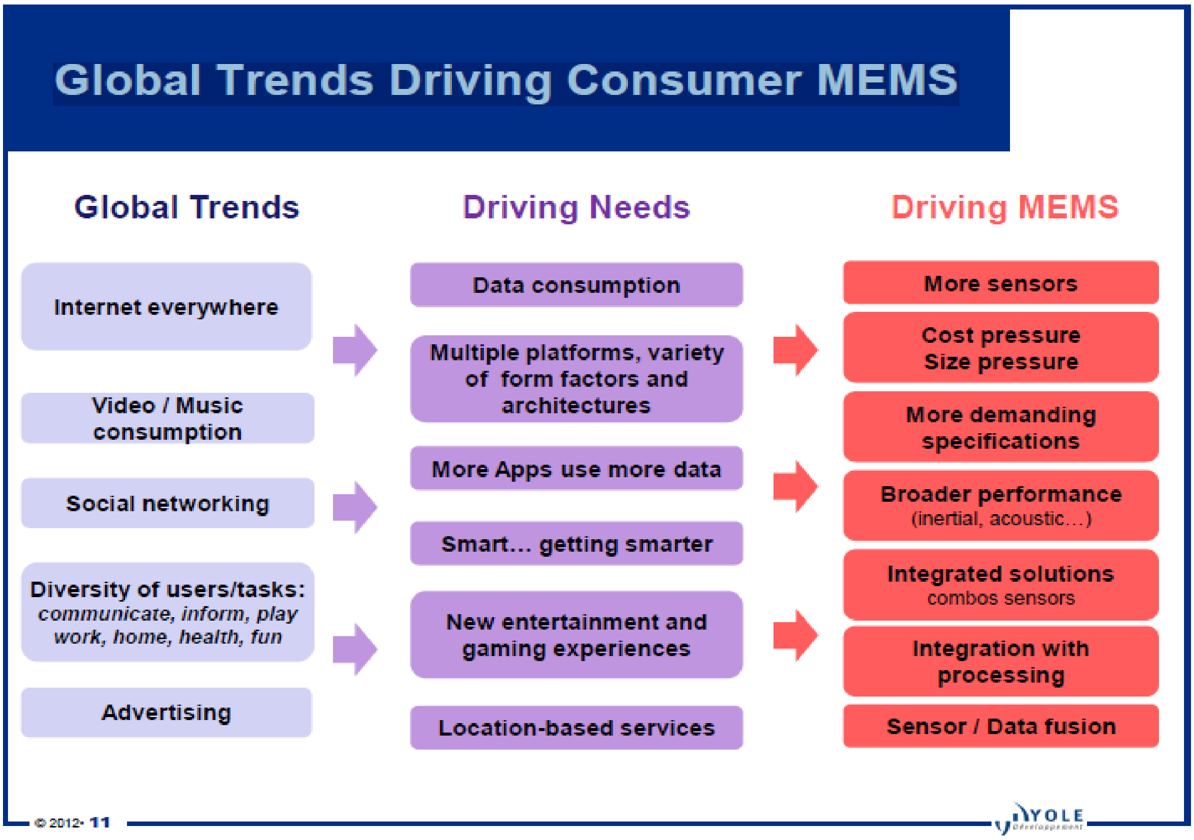

Figure 1.6: *Global trends driving consumer MEMS [43].*

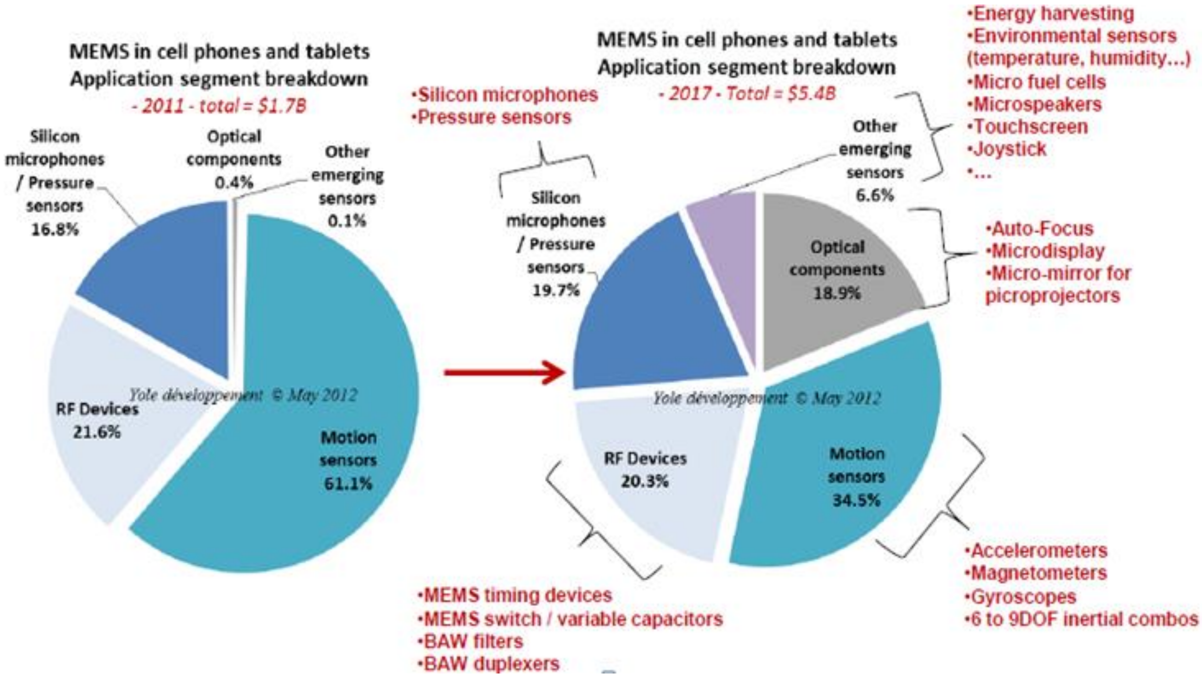

Figure 1.7: *MEMS Product Mix Evolution in Mobile Device [43]*

1.3.4.3 Medical Market

MEMS Medical market has a very high growth potential in the future, global medical market is shown in Figure 1.8. Main categories in Medical Electronics Sector [46] are; implanted products (those devices implanted in a human body), portable products (those devices that are easily transported), diagnostic imaging devices and large scale equipment (e.g., MRI, CT). The market is driven by the increasing demand for miniaturized, low cost devices with high operating speed for diagnostics and individualized treatment. Major challenges for the market include strict regulations, huge investment requirements; the devices have to go through intense approval processes before being commercialized in the markets which are both time-consuming and costly.

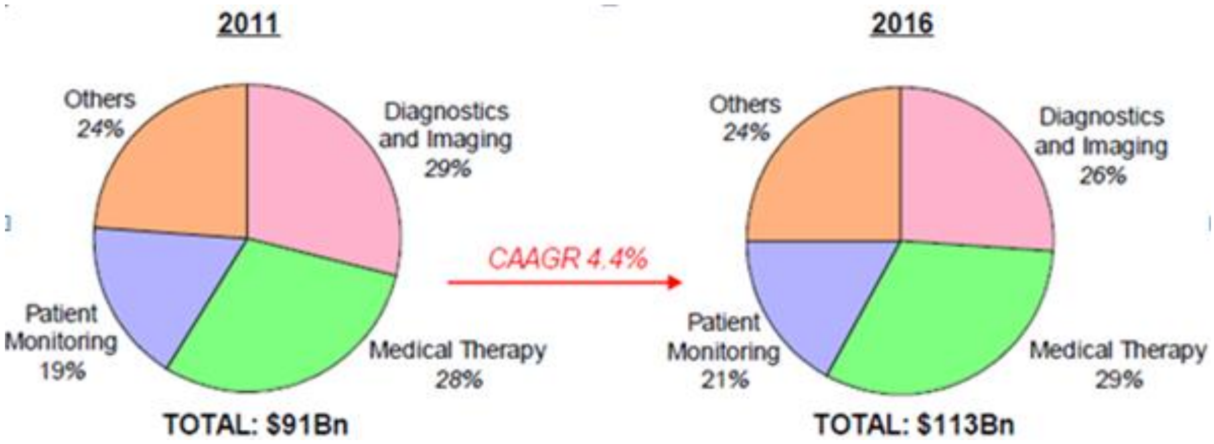

Figure 1.8: *Gloal Medical Electronics Market Summary*[1] *[44]*

1.3.4.4 Military and Aerospace Market

The military and aerospace market is highly driven by performance. The devices must meet the high performance requirements and satisfy the strict specifications and environmental conditions. A wide variety of MEMS devices are used in this market including pressure sensors, inertial sensors, and micro mirrors. MEMS-based inertial measurement units and combo sensors for guidance, and stabilization applications are the greatest grow opportunities for the MEMS within the Military and aerospace market. The devices have particularly high potential in personal navigation systems, typically referred to as inertial navigation systems (INS), which become highly useful in areas not served by reliable GPS.

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[1] ***Diagnostics and Imaging****; Diagnostic instruments provide high resolution pictures of structures inside the body. Example: MRI, X-ray, ultrasound Equipment,* ***Medical Therapy****; Equipment used in the treatment of specific medical conditions Example: defibrillator, hearing aid,* ***Patient Monitoring****; Instruments used to measure and monitor patients' vital signs and other functions. Example: blood glucose, ECG,* ***Others;*** *All other electronics used for medical applications Example: surgical tools, test & analytical, medical IT, biochips, RFID Diagnostics.*

1.3.4.5 Industrial Market

Industrial market is a relatively large MEMS market with high growth prospects in the future. MEMS devices can be used in several industrial areas ranging from process control and industrial automation to energy applications.

Process control and industrial automation is a prominent business, especially wireless monitoring and control system has recently become more popular. In these applications, MEMS sensors, such as pressure sensors, flow sensors and accelerometers are already widely applied. MEMS devices are also used in energy applications such as oil and gas exploration and extracting. In these applications MEMS-based accelerometers and gyroscopes play an important role. In addition, low power MEMS devices can be used for energy conservation purposes in many industrial processes and transportation. An emerging application area is MEMS-based energy harvesting systems. The reliability and performance requirements are much higher in these applications as the devices are typically used under harsh conditions.

1.3.4.6 Telecommunication Market

Telecommunication market is a low volume MEMS market with moderate growth prospects. The largest application area for MEMS devices in the market is optical communication. Currently, there is a heightened expectation for the optical MEMS technology to be applicable in the high volume telecommunication market.

A key driver to the growth is the increasing deployment of fiber-to-the-home technologies to accommodate faster data traffic in networks. In additionally, the wireless market is becoming an interesting sector with new functionality on offer by various RF MEMS components.

1.4 Non-destructive Test Methodology and Challenges

MEMS are the most dynamic industry in terms of developing new technologies for the device and packaging. Development of the MEMS devices which are produced in small size and volume, mass and power consumption generates one of the most challenging tasks in today's micromechanics [1]. In addition to design, analysis, and fabrication capabilities, there is also need for advanced NDT methods to determine the functional characteristics of the devices, to enable optimization of their designs and to demonstrate their reliability. However, using recent advances in photonics, electronics, and computer technology, it is possible to develop a NDT methodology suitable for the evaluation of MEMS. Despite a substantial amount of research in the field, there are still many challenges in energy dissipation in MEMS, which limits their performance, reliability and durability. This is one of the most challenging problems in the developing area of non-destructive test systems and methods.

The NDT plays a critically important role in assuring that the MEMS devices realize their function in a reliable and feasible way [6]. The test samples/systems can be inspected and measured without any damage and with cost effectiveness through NDT that is used to describe: measurements that are more quantitative locate a defect and measure its size, shape, and orientation and determine the material properties, such as fracture toughness, formability, and other physical characteristics. In general the most commonly used NDT inspection methods are:

- **Visual and Optical Testing:** Simply looking at a part to see if surface imperfections visible, using computer controlled camera systems to automatically recognize and measure features of the samples.
- **Radiography:** Use of penetrating X radiation on materials and products to check for defects or to examine internal or hidden features.

- **Ultrasonic Testing:** High-frequency sound waves are transmitted into a material in order to detect imperfections or to locate changes in material properties.
- **Penetrant Testing:** The test object is coated with a solution that contains a visible or fluorescent dye. Excess solution is then removed from the surface of the object but it is left in surface breaking defects. With fluorescent dyes, ultraviolet light is used to make the bleed out fluoresce brightly, thus allowing imperfections to be readily seen.
- **Electromagnetic Testing:** In Eddy current testing, electrical currents are generated in a conductive material by a changing magnetic field. Material defects cause interruptions in the flow of the eddy currents which alert the inspector to the presence of a defect or other change in the material.
- **Hermeticity (Leak) Testing:** Several techniques are used to detect and locate leaks in pressure containment parts, pressure vessels, and structures. Leaks can be detected using containment electronic listening devices, pressure gauge measurements, liquid and gas penetrant techniques.
- **Acoustic Emission Testing:** When a solid material is stressed, impactions within the material emit short bursts of the acoustic energy called "emissions". As in ultrasonic testing, acoustic emissions can be detected by special receivers. Emission sources can be evaluated through the study of their intensity and arrival time to collect information (such as their location) about the sources of the energy.

1.4.1 NDT Issues and Challenge

The demand for NDT/ NDE has been driven by the need for lower cost methods and instruments with greater reliability, sensitivity, user friendliness and high operational speed.

In addition to these needs, the technology is sought for applicability to complex materials and structures, and also a recent challenge for these devices is to move the platform for the application of aerospace [5]. Some of the current issues of NDT/NDE are:

- Two major types of defects are commonly sought to be detected: fatigue cracks and corrosion. Generally, fatigue cracks are relatively easy to determine. But corrosion damage is much more complicated. Detection of the corrosion types may require a different NDT approach due to the unique characteristics that are involved. All existing NDT/NDE methods for detection of corrosion are limited in capability and sensitivity.
- Defect detection and characterization: Defects include delamination's cracking, fiber fracture, fiber pull-out, matrix cracking, inclusions, voids, and impact-damage.
- Material properties characterization: Current destructive test methods are costly and they don't provide direct information about the properties of represented structure.
- Need for rapid large area inspection: Impact damage can have critical effects on the structure capability to operate in service, so there is need for a low-cost system.
- Residual stresses: Current state of the art does not provide the effective means of non-destructive determination of residual stresses.
- Weathering and corrosion damage: Regular NDT methods provide limited and mostly qualitative information about the defects and material properties.

The main challenges of NDT are:

- Research must concentrate on the development of components with a focus on NDT functionality which would lead to affordability of NDT methods to commercial use.
- In future, MEMS technology is expected to yield extremely small NDT instruments.
- Advancement in miniaturized MEMS devices is expected to make great impact on NDT in future.
- The search for smarter methods that can rapidly and inexpensively detect very small defects in complex materials and structures at very high probability and repeatability will continue to be a challenge for NDT.
- Efforts will be made to simplify inspection procedures. Additionally, insignificant tasks and critical decision-making will be performed by computers.

1.5 Thesis Outline

Experimental study implemented with three groups of samples; free standing cantilever

beams, line contact and third group is area (30% and 40%) contact cantilevers. Samples tested by the Q-factor measurement methods which are developed based on Logarithmic Decrement methodology under the vacuum environment.

Test steps are; first step is the definition and implementation of process instruction for the all samples to obtain more reliable results. At the second step samples are tested by Polytec Vibrometer, and produced data for the time domain (velocity - time) measurements, third step was testing the samples under the slight vacuum by using vacuum chamber, and at last step test outputs converted to “*Best fitted to envelope function (BFEF) that has been produced for this experimental study*” and compute the Q-factors for each samples.

The goal of the study was measuring Q-factor for MEMS devices using developed calculation methodology and finding effect of line and area contact phenomenon on Q-factor. Novelty is finding whether the line and area contact improves the Q-factor of MEMS cantilever device.

First chapter gives background information for the MEMS and NDT and brief information about challenges, market and applications. Chapter 2 provides detailed description about relevant theory of the case. Chapter 3 describes the analytical analysis, and calculation model of the Q-factor in details. Chapter 4 describes the Experimental analysis, test methods, and Chapter 5 presents the results of Q-factor calculation based on experimental results. Finally, conclusion remarks and future works are given in Chapter 6.

Chapter II

2 Theory

2.1 Resonance Frequency

Resonance can be defined in physics as "*the tendency of a system to oscillate with greater amplitude at some frequencies than at others*" [54]. Frequencies at which the response amplitude is a relative maximum are known as the resonance frequencies, shown in figure 2.0. At these frequencies, small periodic driving forces can produce large amplitude oscillations, because the system stores vibrational energy [8]. Resonance frequency is by definition; a level of frequency which enable to the largest possible amplitude of oscillating system, so that we are able to know how a system will act when the frequency reaches a specific level.

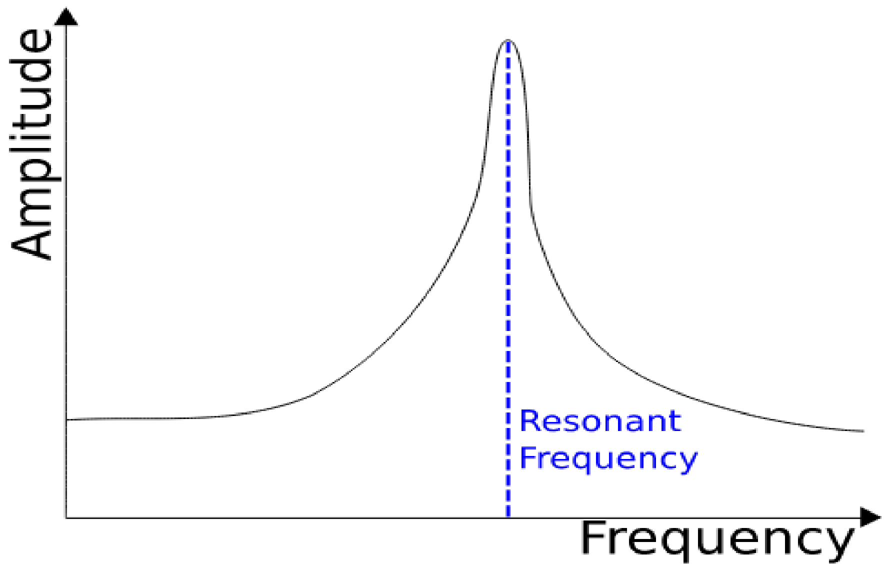


Figure 2.0: *Schematic Resonance Frequency curve*
(http://en.wikibooks.org/wiki/A-level_Physics_(Advancing_Physics)/Resonance)

Most of the literature provides well-known example about the destruction of the Tacoma's Narrow Bridge in Washington shown in Figure 2.1, which was oscillated at almost its resonance frequency. That is why it is highly important to know what the resonance frequency of the oscillating systems is to avoid catastrophic events. In physics, the frequency causes two types of resonance according to their boundary conditions [9]:

- **Pure resonance** occurs when the natural internal frequency ωo matches the natural external frequency ω, in which case all solutions of differential equation are unbounded. Pure resonance never happens in the physical world because damping is always present.
- **Practical resonance** occurs when $c > 0$, only when bounded solutions exist for the forced spring mess systems below:

$$m\,\ddot{x}\,(t) + c\,\dot{x}\,(t) + k\,x\,(t) = F_0 \cos \omega t \qquad (2.1)$$

$$\omega = \sqrt{k/m - c^2/2m^2}, \qquad \text{and} \qquad k/m - c^2/2m^2 > 0 \qquad (2.2)$$

Figure 2.1 *Destruction of the Tocomas Norrow Bridge*
(http://en.wikipedia.org/wiki/Tacoma_Narrows_Bridge-1940)

The resonance frequency of a cantilever can easily be approximated using differential mathematics and some basic boundary conditions. The basic equation is derived in [10] and is shown in equation (2.3):

$$\boldsymbol{\omega_i} = (\boldsymbol{\beta_i l})^{2}\sqrt{\boldsymbol{EI}/\boldsymbol{m\rho A l^4}} \qquad \textbf{(2.3)}$$

In this equation, $\boldsymbol{\omega_i}$ represents the resonance frequency, $\boldsymbol{\beta_i}$ and $\boldsymbol{i}$ number of modes which depends on the boundary conditions (the calculated numerical approximation and the value can be seen in Table 2). $\boldsymbol{E}$ is the Young's modulus of the cantilever, $\boldsymbol{I}$ is the moment of inertia, $\boldsymbol{\rho}$ is the mass density of the cantilever, $\boldsymbol{A}$ is the cross-sectional area of the beam and $\boldsymbol{l}$ is the length of the cantilever.

The representation of these modes for a fixed-free cantilever can be seen in Figure 2.2. The values calculated from Equation (2.3) and Table 2, which gives the resonance frequencies in a vacuum.

Table 2 *Numerical approximation for wave number of fixed-free cantilever*

$\boldsymbol{\beta_i l}$ ($\boldsymbol{i}$: **1, 2, 3, 4**)	**Numerical approximation**
$\boldsymbol{\beta_1 l}$	**1.875104**
$\boldsymbol{\beta_2 l}$	**4.694091**
$\boldsymbol{\beta_3 l}$	**7.854757**
$\boldsymbol{\beta_4 l}$	**10.995541**

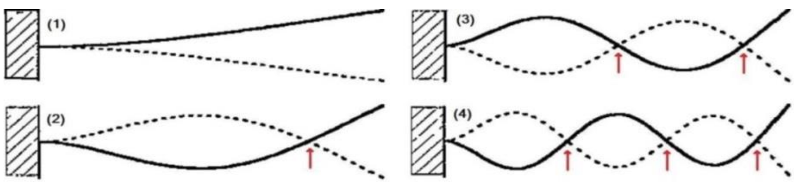


Figure 2.2: *The first four shapes modes* $(i = 1,2,3,4)$ *of a fixed-free cantilever. The red arrows show the nodes of each mode. [10]*

2.2 MEMS Reliability

There are a number of factors that contribute to the reliability of MEMS [11]; packaging (in particular, in bonding and sealing), material characterization relating to operating and environmental conditions, credible design considerations, the techniques for mitigation intrinsic stresses/strains induced by fabrications and testing for reliability.

MEMS design, fabrication, packaging, and reliability testing are relatively new technology and require continuous improvement. MEMS failure and root cause analysis is an important step for tooling, fabrication and design of MEMS in terms of reliability.

MEMS failure mechanisms can be as unique as the devices themselves because each device requires working with the defined environment. Additionally, dynamic of MEMS requires extra care in handling and testing [12].

MEMS components are highly diverse in their application and function. Because of this feature, testers and analysts should be equally diverse and multidisciplinary in their analysis of the devices. Currently most of techniques have been adapted from the integrated circuit industry, but tools and techniques should be developed specifically for testing and diagnosis of failure mechanisms of the MEMS devices. Issues and challenges regarding the reliability testing are:

- One major issue for the testing of MEMS sensors is creating a bench test setup to simulate an environment that the device is designed to sense.
- Leak testing (or hermiticity test technique performed to detect ambient atmosphere leakage paths into the cavity of a hermetic packaging) of devices with very small cavities can be a problem. Detecting small leaks in a system is important for the failure analysis to determine changes in the device sensitivity.

- Dominant failure modes are particle contamination and stiction. The main concerns of MEMS actuators are non-destructive analysis, failure analysis of anti-stiction coatings and films, and dynamics. The challenge for the reliability test is to determine what temperature the thermal actuator increase to when a permanent damage occurs. Thermal analysis of moving components is very difficult.
- Challenge for RF MEMS is non-destructive analysis of an adhesion or cold welds (CW) failure. A common feature of interest in all contact devices is the surface roughness of the contact area. The challenge for the failure analyst is to develop a tool that can perform multiple measurements on single and several devices in parallel at the same time.
- The challenge for failure analysis is to develop a tool or technique that can allow root mean square (RMS) roughness along the entire array of MEMS mirrors in parallel, in several places along those micro mirrors.
- Most of the tools and techniques have not been designed to be used with micro fluidic MEMS. The challenges for the failure analyst include functional and structural analysis while maintaining device and tool integrity, fluid contamination and compatibility with MEMS and analytical tools, de-processing, leak detection, and application of a diagnostic fluid for analysis.
- Bio-MEMS are more difficult to analyze and diagnose due to a required understanding in the device process, operation, and operating environment. The current issues in testing and analyzing the device include biocompatibility, functional testing, and device de-processing. In this field, the challenge is the fact that the analysts must have multidisciplinary background and must be able to work with engineers and biologists [13].

2.2.1 Stiction

The major challenges of MEMS technology are proving its reliability and performance factors. The most important reliability issue is the stiction. The moving parts of MEMS devices like cantilever tend to seize up under the force of sticking and friction [14]. Stiction occurs at all scales, and has a finite effect, based on the effective contact area (true points of contact between two rough surfaces, shown in Figure 2.3, and other parameters)

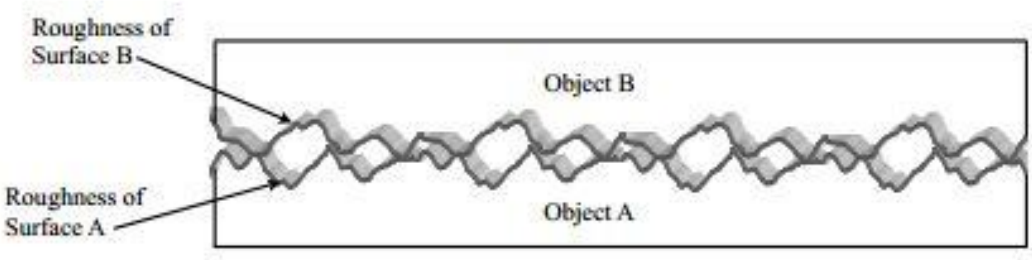


Figure 2.3: *Schematically shown effective contact roughness areas A, and B (http://www.engr.uvic.ca/~mech466/MECH466-Lecture-5.pdf)*

At the micro-scale, the forces associated with the stiction effect are often greater than other micro-forces. As a result, if stiction is present in a micro-system, it can dominate the system [2]. This usually has negative effects, such as micro objects sticking together with no way to separate them, or high amounts of dissipative loss between two objects in sliding contact. Stiction occurs in two stages;

- **Release related stiction** occurs during the process of the sacrificial layer removal in fabrication. It is called primarily capillary forces.
- **In use stiction** is adhesive attraction which exceeds restore force or when surface permanently adheres to each other causing the device failure. Also high humidity and temperature occur in use stiction.

An adhesion-related failure occurs in MEMS when suspended elastic members such as cantilever unexpectedly stick to their substrates. This type of device failure is one of the dominant sources of yield loss in MEMS. Mastrangelo (1997) has done practical and theoretical analysis for the physical mechanism of the failure, and proposed that the failure might result from two different phenomena [15]:

- **Mechanical collapse**: A strong force must be applied to the device to break up the elastic cantilever to contact with substrate.
- **Adhesion to substrate:** When force is released, cantilever and substrate are still not released due to the inter-solid adhesion when the force is released. When one of these stages is eliminated, failure doesn't occur.

The stiction for MEMS will occur upon contact between micro-objects due to the following reasons:

- Electrostatic forces,
- Fluid surface tension effects due to the drying process after the HF release of sacrificial layers.
- Shock loading or rapid acceleration that can bring two surfaces together.
- Inadequate stiffness of supporting micro-beams against gravity or normal operation.
- Desired contact by design.

Once contact has occurred, there are four major phenomena that individually contribute to the "overall effect" of stiction. These are:

1. **Capillary Forces:** Stiction due to capillary force occurs when there is a liquid-solid

interface and acting during the drying process after the release etching. The following picture (Figure. 2.4) schematically shows two parallel plates with a liquid between **them** [3]:

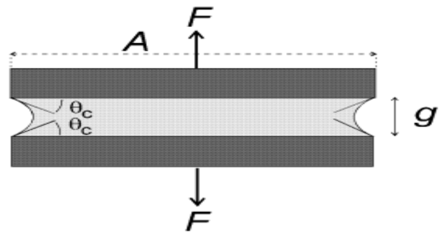


Figure 2.4: A *thin layer of liquid working as an adhesive between two plates. [16])*

θ_C is the contact angle between liquid and solid in air, g is liquid layer thickness, A_w is the wetted area. Force, F, is applied to maintain equilibrium. If θ_C< 90°, then a force "F" will exist between the two plates. The pressure difference between the liquid-air interfaces is given by the equation:

$$\Delta p_{la} = \frac{\gamma_{la}}{r} \quad \textbf{(2.4)}$$

where, (Δp_{la}) pressure difference at liqiuid-air interface, (γ_{la}) surface tension of the liquid – air interface, (*r*) radius of curvature of meniscus of liquid.

From simple geometry it follows that;

$$r = -g / 2 \cos .\ \theta_C \quad \textbf{(2.6)}$$

an external force **F** separating the plates must be applied to counterbalance the capillary pressure forces:

$$F = \Delta p_{la} * A_w = (A_w * \gamma\ la * 2 \cos \theta_C) / g \quad \textbf{(2.7)}$$

2. **Hydrogen Bridging:** Stiction can also occur due to hydrogen bridging. Some materials absorb water to a small depth just below their surface layer, and are said to have "hydrated surfaces". For example, hydrophilic silicon surfaces, under

atmospheric conditions and temperatures well below 200°C, contain adsorbed water layers [16]. When two of these hydrated surfaces are brought into close contact, hydrogen bonds may form between oxygen and the hydrogen atoms of the absorbed water layers in each of the surfaces. This is a chemical bond that will remain, as long as the surfaces remain hydrated.

3. **Electrostatic Attraction:** Electrostatic force can serve two functions in stiction. First, it can act over a distance to bring two micro-objects into contact, and secondly, if there is a dielectric layer of material present between the two bodies in contact, such as silicon dioxide, or other material, the charge between the two bodies may remain for some time. After the contact occurs, the electrostatic charges will dissipate or equalize over time, based on the material dielectric properties, resulting in no net force.

4. **Van der Waals force :** In general, van der Waals forces are defined as including attractions between atoms, molecules, and surfaces. The van der Waals forces between two bodies are caused by mutual electric interaction of the induced dipoles in the two bodies. These bodies can be considered as molecules or grains within a polycrystalline material (also called polysilicon, which is a material consisting of small silicon crystals). The effect of van der Waals force depends on a material's properties, and it is important when strongly polar molecules or elements within materials are in contact. The Interaction energy, $\boldsymbol{E_{vdW}}$, per unit area due to van der Waals interaction between two flat surface in the non-retarded regime (small separation d < 20nm) is given by [16];

$$\boldsymbol{E_{vdW}} = -\frac{\boldsymbol{A_h}}{\boldsymbol{12\pi d^2}} \qquad \textbf{(2.8)}$$

$\boldsymbol{A_h}$ is Hamaker constant (J) 0.4<$\boldsymbol{A_h}$ <4 x10^{-19} and $\boldsymbol{d}$ is the distance between surfaces.

2.2 Energy Loses Mechanism and Q-factor in MEMS

2.3.1 Q-Factor

The Q-factor the rate of energy loss in a resonant circuit [17]. Q-factor can be generally defined for electrical and mechanical components as; *the ratio of the energy stored in a device to the energy dissipated per cycle of resonance.* Key parameters in MEMS devices is the Q-factor and the self-resonance frequency where Q-factor would peak [18].

The higher value of Q-factor caused the higher the micro-system's performance. The method to get high Q-factor is reduce the air damping effect which is the most dominant limitation factor of the Q-factor so that using of vacuum packaging is the preferred way[19].

Some other Q-factor improvement methods have been reported by Zalalutdinov et.al. (2001) in the case of light-activated high frequency modulation obtain improved Q-factor (Q=11000) using a pulsed laser locally heating the device [20] or another study has been done by R. Baskaran et.al (2003), using electrostatic modulation exciting two different modes on a torsional micro resonator [21**].**

The bandwidth, of a damped oscillator is schematically shown in Figure 2.4. The higher the Q-factor is, the narrower and sharper the peak is. Q-factor indicates a lower rate of energy loss relative to the stored energy of the resonator so that the oscillations die out more slowly, in other words high Q-factor has lower damping ratio.

In physics Q-factor is a parameter of an oscillatory system or device, representing the degree to which it is undamped; it can be defined as the relationship between stored energy and energy dissipation per unit time:

$$\boldsymbol{Q} = 2\pi \, \frac{\textbf{Energy Stored}}{\textbf{Energy Dissipated per cycle}} = 2\pi f_r \, \frac{\textbf{Energy Stored}}{\textbf{Power Loss}} \qquad \textbf{(2.9)}$$

$$\boldsymbol{\omega_r} = 2\pi f_r \qquad \textbf{(2.10)}$$

" ω_r" is called the circular or angular frequency," f_r" is called the oscillation frequency or just frequency, ***"r"*** specified resonance.

The Q-factor is a parameter that describes how under damped an oscillating system in Figure 2.5, and also equivalently, characterizes a resonator's bandwidth relative to its center frequency. The bandwidth denoted by $\Delta f = (f_2 - f_1)$, and the Q-factor of the damped oscillator is:

$$Q = f_0 / \Delta f \qquad \textbf{(2.12)}$$

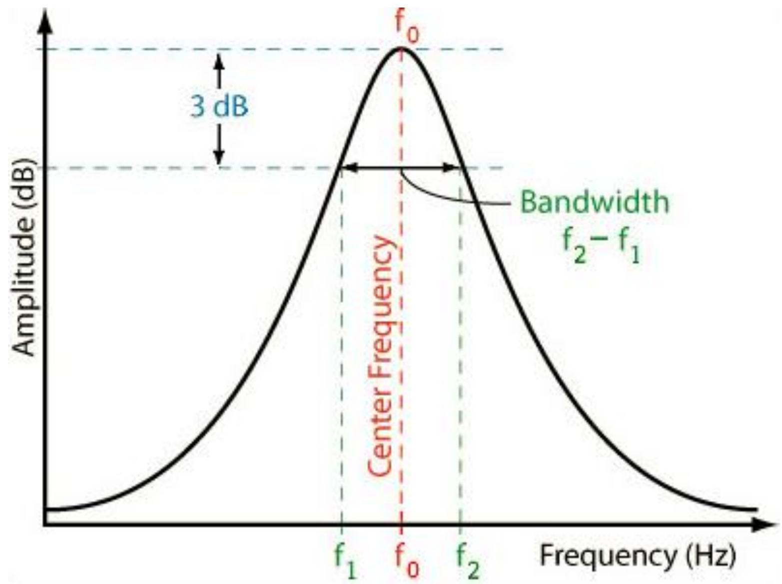


Figure 2.5: *Schematically showing the bandwidth of a damped oscillation (http://www.sengpielaudio.com/calculator-bandwidth.htm)*

2.3.2 Vibration and Damping

Definition of vibration is the periodic back-and-forth motion of an elastic body which oscillates about a position of equilibrium.

Three variables of the vibration are; period, frequency and amplitude. Period is time interval of oscillating system to complete a full cycle of the motion and number of cycles per unit time defines the frequency of the vibrations. Maximum displacement of the system from the equilibrium position is the amplitude of the vibration [55].

In term of physical explanation; a vibrating system must have components that able to store potential energy and release it as kinetic energy in the form of vibration of the mass. The motion of the mass then gives up kinetic energy to the potential energy storing device.

A classic example is provided by a weight suspended from a spring. In equilibrium, the system has minimum energy and the weight is at rest. If the weight is pulled down and released, the system will respond by vibrating vertically. The vibrational properties of engineering devices such as MEMS are often limiting factors in their performance.

Vibrations fall into two categories; free and forced vibration. Free vibrations are oscillations where the total energy stays the same over time. This means that the amplitude of the vibration stays the same. This is a theoretical idea because in real systems the energy is dissipated by the overtime and the amplitude decays to zero, this dissipation of energy is called damping.

Damping is the energy dissipation properties of a material or system under cyclic stress. In general damping is divided into two groups:

- Active damping: Active damping refers to energy dissipation from the system by external means, such as controlled actuator, etc.
- Passive damping: Passive damping refers to energy dissipation within the structure by add-on damping devices such as isolator, by structural joints and supports, or by structural member's internal damping.

From a theoretical perspective, there are different methods to measure the damping. These methods are divided into two main groups regarding whether the response of the system is expressed as a function of time or as a function of frequency [22].

The first group of methods is mainly time-domain response like logarithmic decrement method, step-response method and hysteretic loop method. Second group is based on frequency domain response, such as magnification Q-factor method and bandwidth methods. Among these methods, logarithmic decrement (or free Ring-down) method and bandwidth are the most common methods to measure the damping. The measurement technique of the Q-factor of MEMS will be presented below which has been developed and implemented for this project.

2.3.2.1 Squeeze - Film Damping (SFD)

Almost all MEMS devices required high performance criteria. In particular, MEMS switches required high switching speed, resonant cantilever sensors and gyroscopes required large responses, and MEMS accelerometers require controlled damping. All these needs can only be satisfied by improving and realizing high Q-factor.

Energy loss mechanism in a MEMS device contains a variety of damping factors but experimental and computing studies show us that SFD is the dominant energy loss factor. Therefore, SFD; determines the performance of MEMS / NEMS devices', because it is able to reduce Q-factor from several thousand to a few tens.

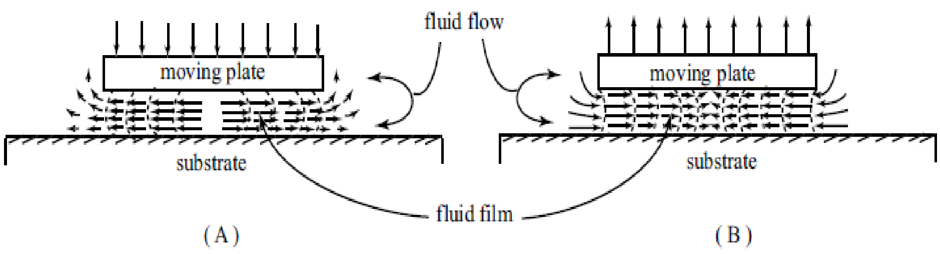


Figure 2.6: *A schematic diagram of SFD flow as a plate moves (a) downward; (b) upward [23]*

In SFD, a MEMS plate moves against a fixed surface and the gas in between generates a viscous damping through resistance to motion, as can be seen in the schematic diagram in Figure 2.6.

Two particular gas regimes will be analyzed; namely continuum flow regime and free molecular flow regime:

1. **Continuum flow regime**: Gas pressure is close to atmospheric pressure and the gap is considerably larger than free molecular path of gas molecules, in this case the gas behaves as a continuum, and approaches related to continuum gas models are applicable [26].
2. **Free molecular flow regime**: The fluid dynamics of gas where the mean free path of molecules is larger than the size of the object under the test; also is called the regime of high vacuum [25]. Especially in small scale, for example when the characteristic length of MEMS device get smaller and closer to the mean free path of gas molecules inside the MEMS device, the fluid will change from slip-flow regime to transition regime and free molecular flow regime, the gas molecules doesn't move one after another as in continuum flow.

The Knudsen number $\boldsymbol{K_n}$ is an indicator to determine the flow from continuum to free molecular flow, shown in Figure 2.7.

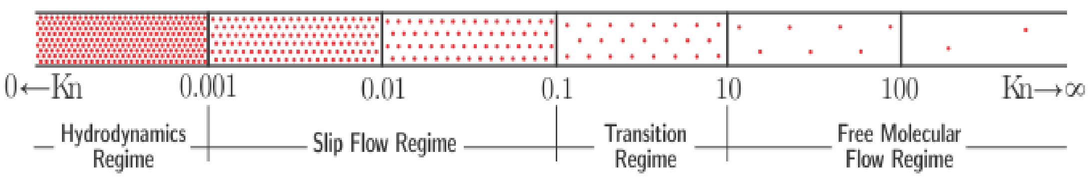


Figure 2.7: *Flow regimes for different Knudsen Number [23]*

The $\boldsymbol{K_n}$ is a dimensionless number defined as the ratio of the molecular mean free path to gap of the plates;

$$\boldsymbol{K_n} = \lambda / \mathbf{L} \qquad \textbf{(2.13)}$$

where; λ is mean free path of molecule inside of the MEMS, **L** is the characteristic length of MEMS device (gap).

Application of $\boldsymbol{K_n}$ is useful for determining whether it is free molecular regime (K_n>1) or continuum flow regime ($\boldsymbol{K_n}$< 1); in other words, whether to use statistical or continuum fluid dynamics. Mostly MEMS and NEMS devices are designed assuming continuum flow regime.

Squeeze film damping is important in the design of MEMS with high Q-factor. We need more developed models for predicting and designing MEMS device.

Current model issues are:

- Finite element and reduced order models are available based on continuum mechanics. However these models are not able to produce correct results for the free molecule regime.
- Knudsen number determines the damping regime but when the gap is not much larger than the mean free pad, experimental data is needed.
- Sumali reported that models *(Christian-1966, Kadar et al.-1966, Li etal.-1999)* have been used to explain data measured on SFD only [25.1]. Because these are molecular based models rather than molecular dynamic models, they give higher Q-factor (lower squeeze film damping) value than measured.
- Sumali et al. [24, 25] reported that, for the atmospheric pressure the simplest model introduced by Andrews et al. (1993) is as good as any sophisticated model.

In high squeeze number regime (low pressure and high frequency), Veijola (2004) model appears to match experimental data accurately [24, 25].

- Developing new models need to continue through research including the use of simulation techniques like Monte Carlo simulation.

2.3.2 Q-Factor and Damping

In physical systems, damping is produced by the processes that dissipate the energy stored in the oscillation. The damping of a system, shown in Figure 2.8, can be described as being one of the followings:

- **Over damped:** ($\boldsymbol{\zeta > 1}$)The system returns exponential decay[2], to equilibrium without oscillating
- **Critically damped:** ($\boldsymbol{\zeta = 1}$)The system returns to equilibrium as quickly as possible without oscillating
- **Underdamped:** ($0 \leqslant \boldsymbol{\zeta < 1}$)The system oscillates with the amplitude gradually decreasing to zero
- **Undamped:** ($\boldsymbol{\zeta = 0}$)The system oscillates at its natural resonant frequency (ω_o).

Different levels of damping are desired for different types of systems. A system with low Q-factor **(< ½)** is said to be over damped system, and such a system doesn't oscillate. When displaced from its equilibrium it returns to it by exponential decay, approaching the steady state value asymptotically [27].

[2] A quantity is subject to **exponential decay** if it decreases at a rate proportional to its current value. Symbolically, this process can be expressed by the following differential equation
dN/dt = -λ N , The solution to this equation is: Exponential rate of change N (t) =N_0 $e^{-\lambda t}$
where N is the quantity and λ (lambda) is a positive rate called the exponential decay constant.

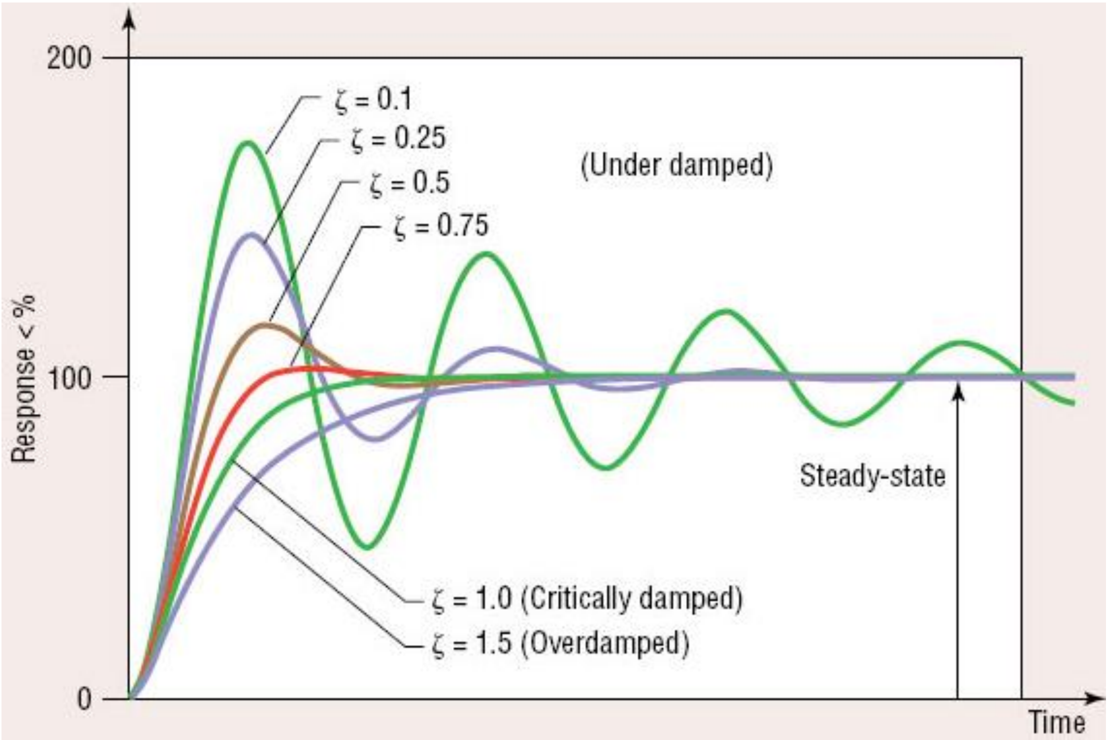


Figure 2.8: Effect of damping
(http://www.audizine.com/forum/showthread.php/582268-koni-yellow-shocks-stock-springs-experience)

A system with high Q-factor **(> ½)** is said to be an under damped systems combining oscillation at a specific frequency with decay of the amplitude of the signal. Under damped systems with a low Q-factor (a little above of ½) may oscillate only once or a few times before damping out. As the quality factor increases, the amount of damping decreases. A high-quality bell rings with a single pure tone for a very long time after being struck.

A system with an intermediate Q-factor (= ½) is said to be a critically damped system like an over damp system, the output does not oscillate, and does not overshoot its steady-state output (i.e., it approaches the steady-state asymptotically).

Physically, Q-factor is the ratio of the total energy stored; $\mathbf{U_s}$ realized by the elastic spring

$$U_s = \frac{1}{2} k\, x^2 \tag{2.14}$$

divided by the energy lost per cycle [28]:

$$U_d = \pi c \omega x^2 \tag{2.15}$$

or more specifically, the ratio of the stored energy to the energy dissipated over one radian of the oscillations [28].

$$Q = 2\pi \frac{U_s}{U_d} \tag{2.16}$$

if we substitute values of (**2.14**) and (**2.15**) into equation **(2.16);** we can calculate the Q-factor equation as:

$$Q = \frac{1}{2\zeta} \tag{2.17}$$

Q-factor is dimensionless parameter that compares the exponentially time constant **(τ)** for decay of an oscillating system's amplitude to its period. Equivalently, it compares the frequency at which a system oscillates to the rate at which it dissipates its energy.

The Q-factor is approximately the number of oscillations required to reduce the system's energy to" $e^{-2\pi}$ "(about 1/535) of its original energy [29].

2.3.2.1 Noise and Challenges

The purpose of this section is giving brief information about noise, because it is critically important for MEMS devices' performance. Due to the miniaturization of the MEMS devices such as smaller size masses and their parts can bring both electrical and non-electrical mechanism which is caused noise effects that limits the performance of MEMS [30].

In general, noise is unwanted electrical or electromagnetic energy that degrades the quality of signals and data. There are two basic and inevitable reasons for the noise, these are first; basic physical entities such as electrons, atom, and molecules and the number of units of variance inevitable, and second the energies associated with the particles, photons and other quanta also have unavoidable distribution**.** The negative effect of noise on MEMS can be divided into two categories:

- The first category pertains to the degradation of performance such as decline in output of acoustic system. In general quality of the output of any actuator can be affected by noise.
- The second category is degrading or limiting the output of sensors or measurement systems that turn any of the external effect into information.

In general, noise in MEMS has two origins; external sources due to the ambient electromagnetic fields or mechanical motions, especially sound and vibration can limit the performance system, and internal sources provide limiting on the device performance.

There are three main noise mechanisms:

- **Electronic noises**, also called as thermal (Johnson) noise can occur due to the temperature induced fluctuation in carrier densities. Generation-recombination noise caused by random production and annihilation of electron-hole pairs in semiconductors), and flicker noise; which varies inversely with frequency ***(1/f)*** and is due to variable trapping on release of carries in any conductor.
- **Mechanical noises**, also known as Brownian or random walk noise. This kind of noise is dynamic unbalanced force caused by random impact of molecules on a small particle or structure. Adsorption-desorption noise: is closely related to Brownian motion.
- **Optical noise** which is noise in intensity. An important type of optimal noise is an optical beam's noise in its intensity.

Challenges of the noise:

- The subject of noise needs to be examined in depth through a systematic literature review and a series of experimental studies.
- The reduction of internal noise from various basic mechanisms is an important challenge to the MEMS researchers and designer.
- RF MEMS, high frequency resonators are more susceptible to mechanical noise than other class of MEMS.
- Need for theoretical and experimental works on external and internal inevitable sources especially for very small nano scale components.
- Advanced Monte-Carlo simulation methods, reliability analysis and developed test methods with test instruments suitable for this area and molecular dynamics computation

Chapter III

3.0 Theoretical Analysis of Q-Factor

In section 2.3 we discussed energy loss mechanisms and damping of linear dynamic systems. In this section I will focus on the methodologies for the identification of damping parameters through experimental measurement. Several methods are available for identifying the damping parameters for linear and non-linear models [31]. For linear damping models these methods can be broadly classified as:

- Methods based on **transient response of the system**, also known as logarithmic decrement or ring-down and calculating based on time domain. For applicability of this method the decay must be exponential.
- Methods based on **harmonic response of system**, also known as bandwidth methods. These methods are based on calculating the half power points and bandwidth from the frequency response curve.
- Methods based on **energy dissipation of the system**; the total energy of a system never change according to the energy conservation law, but, can be change form, like potential energy can convert to any other energy form like kinetic energy it is said to be conserved overtime. Differential equation of motion is established by using the principle of energy conservation (equivalent to Newton's law for conservation system) that sum of potential (U) and kinetic energy (T) of particle remains constant at each instant of time throughout the partial motion. (U+T= constant)

3.1 Logarithmic Decrement Method

The logarithmic decrement method is the most popular method to measure the damping ratio for a single-linear-viscous-damping model [41]. The decay response of model can be expressed as following equations [37] and illustrated in Figure 3.1:

$$X\,(t) = A\; e^{-\zeta\omega_n t} \sin\,(\omega_d t + \varphi) \qquad \textbf{(3.1)}$$

$$\omega_d = \omega_n\sqrt{1-\zeta^2} \qquad \textbf{(3.2)}$$

where A is the amplitude, ζ is the damping ratio, ω_d is the damped circular frequency, and φ is the phase angle of damped oscillations. The natural frequency ω_n for a cantilever beam can be calculated following the equation:

$$\omega_n = \sqrt{\frac{k}{m}} \;=\; \sqrt{\frac{3I\,E}{m\,l^3}} \qquad \textbf{(3.3)}$$

where *l is* the length of the beam, E is the young modulus, I is the moment of Inertia of the cross sectional area, m is the mass.

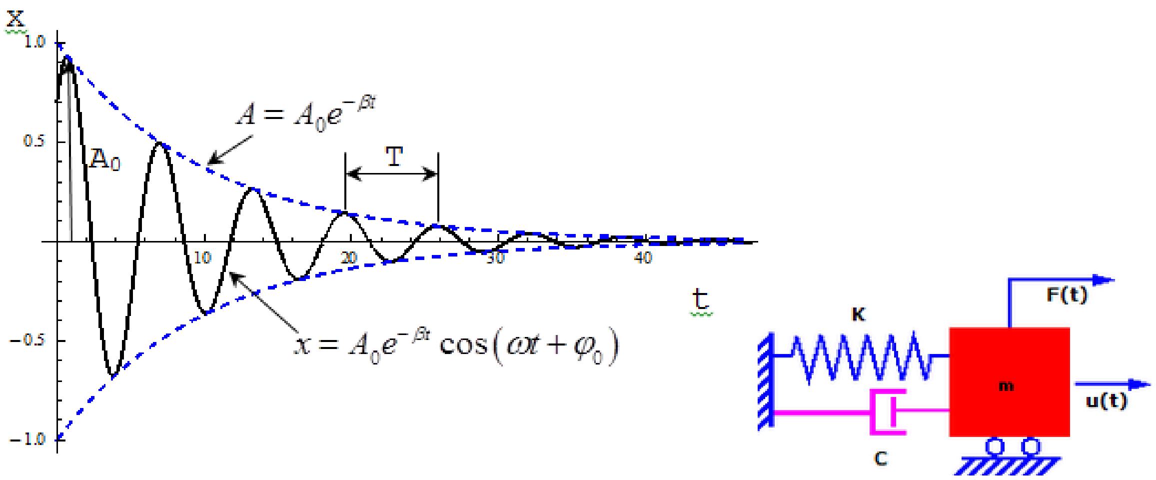
The period T, and ω_n can be measured with stopwatch for vibrations and or if the amplitude is very small, can be measured by the sophisticated time and frequency measurement devices

$$T = \frac{2\pi}{\omega} \;=\; 2\pi\,\sqrt{\frac{m\,l^3}{3\,E\,I}} \qquad \textbf{(3.4)}$$

Damping ratio is the most difficult quantity to determine since it needs a dynamic test to measure it. Record of response of the underdamped system can be used to determine the damping ratio. Decay envelope denoted by the dashed line in Figure. 3.1 for underdamped system are:

$$\textit{Envelope curve formula} = A\; e^{-\zeta\omega_n t} \qquad \textbf{(3.5)}$$

The measured points; $x\,(t_0),\ x\,(t_1)\ \ldots\ x\,(t_n)$, are then curve fit to: $Ae^{-\zeta\omega_n t_1},\ Ae^{-\zeta\omega_n t_n}$



(a) (b)

Figure 3.1: *Schematic views of (a) envelope curve and a single DOF system (b)*

This will yield a value for the coefficient " $\zeta\omega_n$". If we know **"*m* and *k*", "ζ and *c*"** can be determined from" $\zeta\omega_n$". This approach also leads to concept of logarithmic decrement, denoted by" δ "and defined by:

$$\delta = \ln \frac{x(t)}{x(t+T)} \qquad \textbf{(3.6)}$$

Substitution of equation (3.1) into equation (3.6) yields:

$$\delta = \ln \frac{A\, e^{-\zeta\omega_n t} \sin\,(\omega_d t+\varphi)}{A\, e^{-\zeta\omega_n (t+T)} \sin\,(\omega_d t+\omega_d T+\varphi)} \qquad \textbf{(3.7)}$$

Since; $\omega_d T = 2\pi$, the logarithmic decrement can be expressed in the following formula:

$$\delta = \ln e^{\zeta\omega_n T} = \zeta\omega_n T = \frac{2\,\pi\,\zeta}{\sqrt{1-\zeta^2}} \qquad \textbf{(3.8)}$$

The damping coefficient "*c*" can be found if the mass ***m*,** spring constant ***k*** and damping ratio ζ are known by using following equation:

$$c = 2\,\zeta\,\sqrt{m\,k} \qquad \textbf{(3.9)}$$

In this study, the different configuration MEMS cantilever samples were experimentally tested under the vacuumed environment and time domain output of vibrometer analyzed by using new techniques which was based on logarithmic decrement methods denoted by ***BFEF*** methods.

3.2 Principle of Measurement Techniques

Damping is difficult to determine because it needs a dynamic test to measure it. Mostly we estimate the Q-factor by using different techniques and approach. Most common method to roughly estimation Q-factor is simply counting the peak points of the damping curve (Envelope Curve).

3.2.1 Best Fit for Envelop Function Approach

A record of the displacement (x_n) and / or velocity (v_n) can be used to determine damping [33]. In our case we will use the envelope curve of the exponential decay to measure the Q-factor. This approach follows the logarithmic decrement concept [37]. It is derived from the equation for linear under damped free response **(3.1)** where the period is related to the frequency of oscillation by:

$$T_d = \frac{1}{f} = \frac{2\pi}{\omega_d} \quad \textbf{(3.4)}$$

ζ is obtained from equation **(2.17)**, and A, φ are constants of integration obtained from the initial conditions. Therefore using equations; **(3.1)** and **(3.4)** we can re-write a similar equation to the time envelope formula **(3.5)** as:

$$\text{A (t)} = A_o\, e^{\frac{-\pi f t}{Q}} \quad \textbf{(3.10)}$$

Theoretically, observing that the first peak of the vibration occurs at, ***t = T/4***, if we substitute these values into equation **(3.10)**; we can calculate the velocity at the first peak point:

$$A\,(T/4) = v_0 = A_0\, e^{-\frac{\pi}{4Q}} \quad \textbf{(3.11)}$$

However, due to noise, environmental effects and random distribution of experimental data the real system doesn't exhibit a perfect envelope curve. To solve this problem and to plot an appropriate envelope-curve a linear regression [36] approach can be used and will be described following section as third measurement method of Q-factor.

Technically, the envelope curve can be obtained by connecting the peak points of the damping curve to each other. To do this, and to account for the experimental variance, we will use a best-fit approach that accounts for all the peak velocities in the data set.

Notice that the envelope function in equation **(3.10)** has three parameters: A_0, f and Q. The frequency, f, is easily estimated from the data by determining the time it takes to complete a certain number of complete cycles. The other two parameters can be estimated by transforming the envelope function into "a linear equation" and then; applying a linear regression method. Figure 3.1 shows the results of a real test case with the best-fit envelope function drawn in green based on the linear regression method. We start with the general linear equation:

$$Y = m\,X + n \tag{3.12}$$

To transform equation (3.11) to a linear format, take the natural logarithm of both sides of the equation and simplify:

$$\ln A\,(t) = -\frac{\pi f}{Q}\,t + \ln A_0 \tag{3.13}$$

Comparing equations (3.12) and (3.13) we can see that:

$$X \equiv t \tag{3.14}$$

the independent variable X is untransformed,

$$Y \equiv \ln A\,(t) \tag{3.15}$$

the transformed variable Y is the natural log of the peak velocities,

the slope of the linear system is:

$$m = -\frac{\pi f}{Q} \quad \textbf{(3.16)}$$

the intercept of the linear system is:

$$n = Ln\, A_0 \quad \textbf{(3.17)}$$

This transformation of the envelope function to a linear system is equivalent to plotting the curve on a natural log scale along the velocity axis. The slope and intercept of the linear regression line of the transformed system are easy to calculate based on the following formulas:

$$m = \frac{\mathrm{N}(\sum X.Y) - (\sum X)(\sum Y)}{\mathrm{N}(\sum X^2) - (\sum X)^2} \quad \textbf{(3.18)}$$

$$n = \bar{Y} - m\,(\bar{X}) \quad \textbf{(3.19)}$$

The transformed variable, ***Y,*** is the natural log of peak velocities. ***X,*** is the independent variable, time ***t***, of the corresponding peaks, ***N*** is the total number of peak points in the data set**,** ***X-bar*** and ***Y-bar*** in equation **(3.19)** are the arithmetic average of each variable.

Once we have the slope and intercept from the linear system, we can substitute the results into **(3.16)** and **(3.17)** to compute the envelope curve parameters A_0 and ***Q***. This calculation is easily made by software and furthermore, once it has estimated ***f,*** A_0 and ***Q*** the software can easily plot the best-fit envelope curve, in Figure. 3.1.

This method based on the free ring-down (logarithmic decrement) calculation method of Q-factor. The result can be found in the *"Peak Detection Method*" sheet which is second method of estimation Q-factor. This method relies upon filtering the velocity as before to remove noise. Then it detects the cross-over points from positive to negative. Finally it finds the absolute maxima in velocity between those points. So as long as there is enough data and the noise filtering threshold is low enough without being too low, the spreadsheet will detect up to 10 peaks.

A workbook that automates the calculation of Q-factor based on peak counting and peak velocity detections have been formulated and are ready to use. In order to keep the application simple, the system was built based on the logarithmic decrement method of calculating the Q-factor. (This system can be developed to be used for the different devices and measurement of their performance criteria and also adoptable for the other Q-factor calculation methodologies as future work)

Only peak detection on the positively directed peaks was performed.

The workbook contains following process steps:

1. **Importing data step**: This is where the data is imported from the Polytec system output.
2. **Counting peaks (first method) step**: This is where some preliminary filtering and data manipulation occurs and can be safely ignored. Result of this step gives an estimation of the Q-factor.
3. **Detecting peaks (second method) step**: This is where the final analysis and calculations are performed. The Q-factor can be read from the cells highlighted in green. It is possible to quickly change the filtering threshold by modifying the yellow cell as a percentage of the maximum velocity and quickly verify whether the imported data looks good and how well the peak detection is by looking at the graph and playing with the filtering threshold. Currently, the number of data points must be less than or equal to 10,000. All data past 10,000 points will be ignored.
4. **Best fit Q factor calculation (third method) method**: The resulting data is fed into the best fit Q-factor computing system to get a regression line using linear regression methods. Once the linear regression equation is obtained, it is turned

back to the envelope curves in Figure 5.1, 5.2, 5.3, and 5.4 which will be best fitted to the Q-factor envelope graph and also result of computed Q-factor of the sample given as a table automatically in Table 3.

Chapter IV

4 Experimental Analysis

MEMS are a promising platform for next generation sensors and actuators. Impressive developments in recent years have been done and the results are seen in industrial applications. Despite a substantial amount of research in the field, there are still many challenges in energy dissipation in MEMS, which limits their performance and reliability. This is one of the most challenging problems in the developing area of non-destructive test systems and methods [32].

This project demonstrates an experimental set-up that utilizes a Scanning Laser Doppler Vibrometer (LDV) to produce experimental data velocity-time domain to calculate the Q [33].

The Q-factor was calculated using different methods for three cases: cantilever beam MEMS actuator; in free standing, in line-contact, and in area-contact. Experimental results show that Q-factor quadruples as contact evolves from line to area contact.

4.1 Introduction

Castellini et al. (2002) presented a flexible work station for characterization of MEMS devices [34]. The key features of this system is “Microscope scanning laser Doppler vibrometer”, including; micro-positioners, digital signal processing, image acquisition and processing.

Cantilever beam equations can be used to calculate micro cantilever stiffness, natural frequency, pull-in voltage, and magnitude of the activation force. However, fabrication tolerances and accuracy of material properties have deep influence on the dynamics and mechanical performance of micro switches. That is the reason why experimental measurement gives more accurate results.

The purpose of experimental work is to measure Q-factor of MEMS devices and to analyze the effect of the line and area contacted cantilever beams to the Q-factor using a micro scanning microscope under the soft vacuum with vacuum chamber.

4.2 Experimental Set-up

The work station, shown in Figure 4.1, is composed of Microscope scanning laser Doppler vibrometer Polytec MSV-400, fiber optic Interferometer, microscope scanner, positioning of the sample, vacuum system and measurement and calculation of Q-factor.

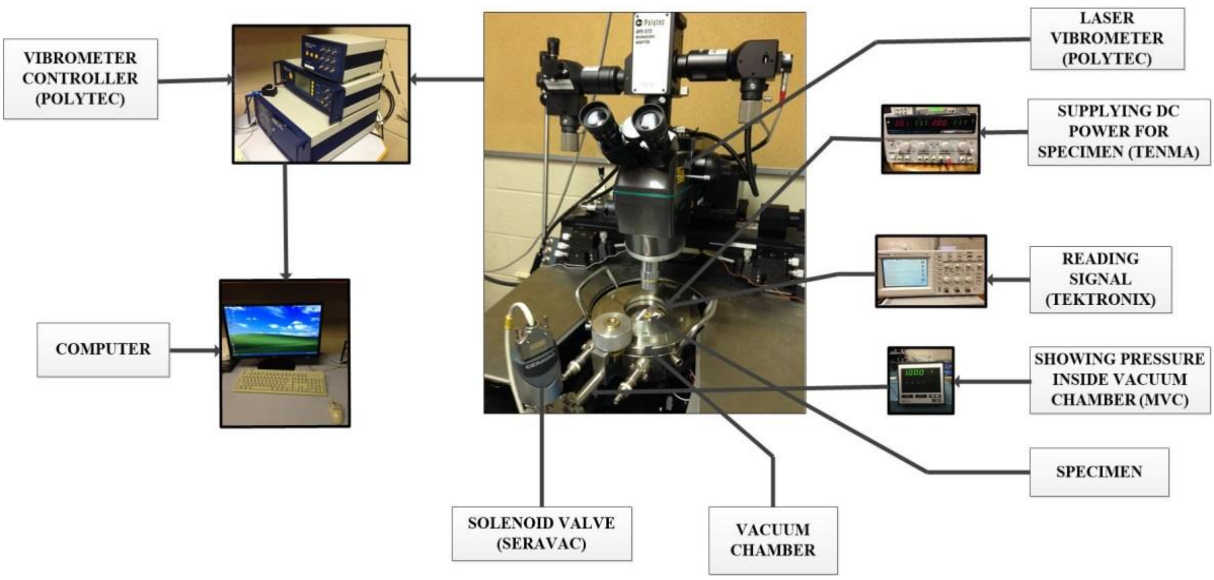


Figure 4.1: *The general view of dynamic work station.*

Polytec LDV is a tool for dynamic characterization of MEMS and a measurement technique for non-contact, out-of-plane deflection of MEMS devices. The advantages of LDV for microscope-based measurements are real-time analog output, high resolution (picometer), small spot size (μm), wide frequency range (MHz), wide dynamic range (160 dB) and high accuracy. By coupling the laser beam into a microscope and using piezo-based scanners to position it in the x and y direction within the full area measurement at the microscopic scale. Scan measurements are taken on a point-by-point basis to measure the velocity field of the structure. Fiber interferometers are used to measure small parts where relative motions between two points need to be measured[33].

In this work, the experiment was conducted in vacuum (0.966 and 1.4 Torr) to decreased SFD effects, and thus obtained a better signal-to-noise ratio. Actually, SFD effects start to show up for pressures between 0.01 and 10 mbar.

Vacuum system set-up by using a custom-made vacuum chamber and vacuum pump, vacuum gage controller and solenoid valve, shown in Figure 4.2.

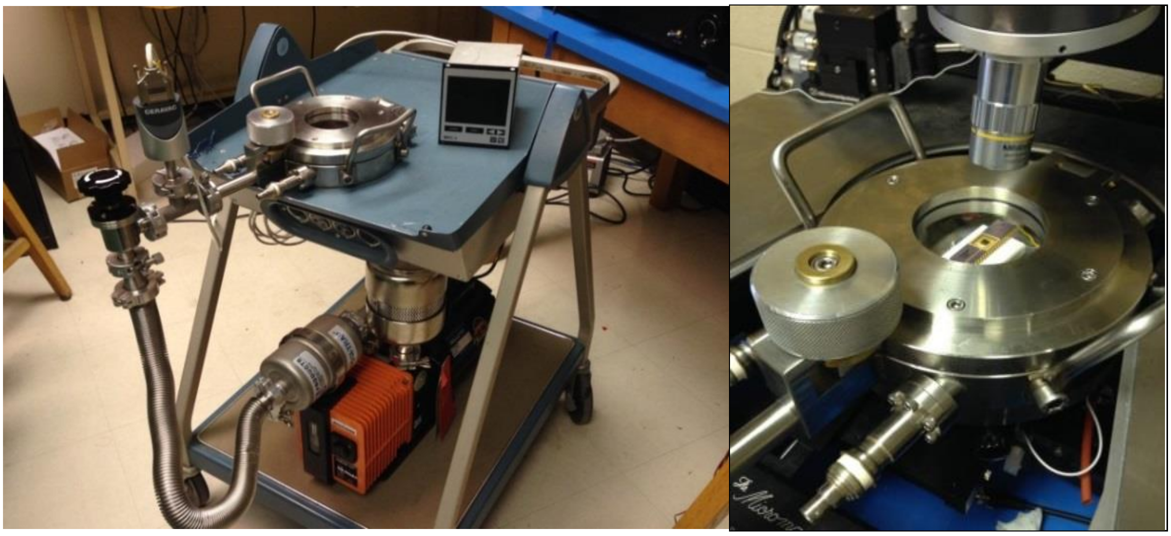


Figure 4.2: *The vacuum equipment* and *vacuum chambers with the sample*.

The results revealed a negative correlation between the two such that decreasing the pressure increases the Q-factor [35].

4.3 Experimental Procedure

4.3.1 Representative Samples

The beams are fabricated using Poly MUMP's process. They are made of poly silicon of density. Experiment study performed with number of MEMS cantilevers. Figure 4.4, shows schematically view of the samples and where dimensions are: contact of active length L =175μm fabricated parallel to a substrate in such a way that separation between the electrodes, h. Other dimensions are: capacitor gap h = 1.5 µm; thickness t = 1.5 µm; width W = 10 µm, adhesion area; 10xd. The material type is SiO_2 and density 2330 kg /m^3, elastic modulus 160Gpa. Figure 4.5, 4.6, 4.7 show pictures of different configuration cantilever beams with the actuation bonding wires.

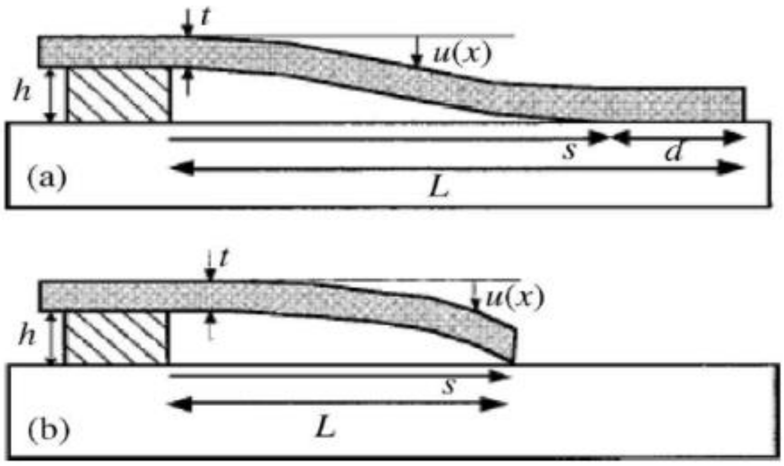


Figure 4.4: *(a) Area Contact (S-shaped) cantilever adhered to the substrate (b) Line Contact (arc-shaped) cantilever adhered to the substrate only very near its tip [4]*

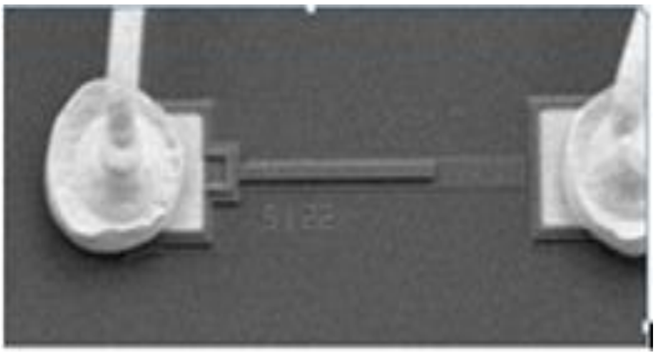


Figure 4.5: *SEM picture of free standing sample (A41-F-V-5DC-2.5Vpp-0.1 KHz).*

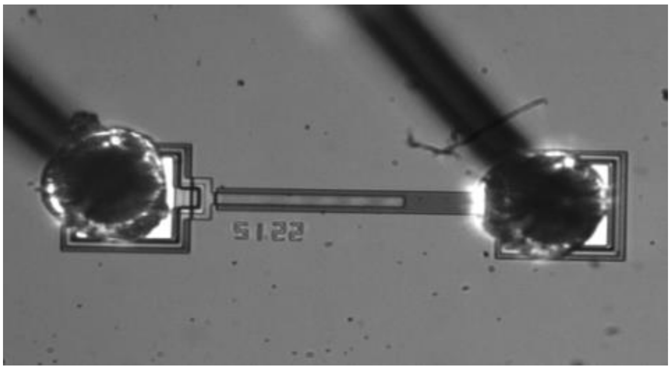


Figure 4.6: *The view of Line contact cantilever (A12-L-V-16DC-2.5Vpp-2.5Hz)*

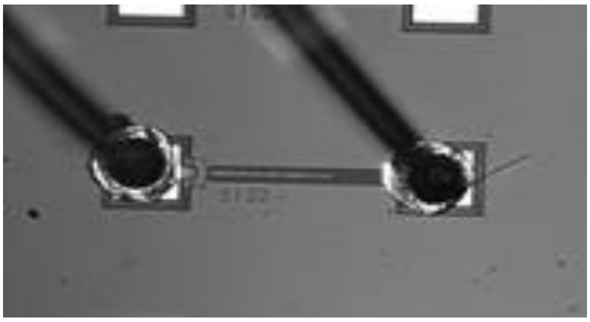


Figure 4.7: *The view of area contact cantilever ((A12-A40%-V-20.5DC-2Vpp-2.5KHz)*

Data for this analysis was collected synchronously with the experiments conducted in to ensure consistency. The laser spot of the LDV was focused as close to the tip of the switches as possible, while avoiding the contact pad. Note that the raw measurement data is velocity vs. time, which we integrate to provided displacement vs. time.

Code description

Example: 41-A40%-F-16 DC-2Vpp-0.7KHz.-Pulse 1%-T

all numbers of the code denoted by: 1-2-3-4-5-6-7-8-9-10

Sample group code on the map description (key) due to the denoted numbers:

1; *Column number* (4), **2**; *Row number* (1), **3**; *A; Area contacted, F; free standing, L; Line contacted, B; Burned*, **4**; *Contacted percentage for area or length contacted cantilevers only (40%)*, **5**; *Test conditions F; P atm V; Vacuum (F)*, **6**; *DC Actuation voltage value (16)*,
7; *Peak to peak in AS Voltage in Volt (2)*, **8**; *Frequency value in Hz Cycle per sec (0.7)*, **9**; *Pulse (1%)*, **10**; *Test Type T; Time domain, FFT; Frequency Domain*

Samples list by Codes

a. A41-F-V-5DC-2.5Vpp-0.1KHz Pulse 1% T/FFT

b. A41-F-V-5DC-2.5Vpp-0.1KHz. Pulse 1% T/FFT

c. A12-L-V-16DC-2Vpp-2.5Hz- Pulse 1% T /FFT

d. A12-A30%-V-16DC-2Vpp-2.5KHz. Pulse 1% T/FFT

e. A12-A40%-V-20DC-2Vpp-3KHz. Pulse 1% T/FFT

4.3.2 Test Procedure

The experimental procedure can be broken into three main steps:

1. Vacuum chamber is mounted on and aligned to the interferometer and samples were placed in the vacuum chamber with a device holder (die) and connected all ground and power cables. A view port on the side of chamber allows the use of external laser

Doppler vibrometre to measure the cantilever motion. The samples tested under the vacuum (0.966/1.4 torr).

2. Electrostatic voltage was increased in small level till to reach the free end of cantilever in contact to substrate. Drive excitation (Pull-in electrostatic voltage) was produced by applying electrostatic voltage to the die mounted. The excitation was stopped suddenly and cantilever motion was measured as amplitude decayed.
3. Getting preferred data such as time domain and/or frequency domain. In our case we produced time domain data to compute the Q-factor factor using ring down method

Chapter V

5 Results and Discussion

The work station was set-up in order to obtain very flexible experimental system for dynamic analysis and measure the performance criteria such as Q-factor of the MEMS devices**.** The system is controlled by Polytec software 9.0 this is ready for further development and integration with other system. Also experimental studies have demonstrated that the LDV is a good tool for measurement of the Q-factor which is the one of performance criteria of the MEMS devices in micro scale. It is possible to perform measurement in working vacuum conditions because of its non-contact features.

Different configuration and a number of MEMS cantilever for each configuration were tested and generated the velocity as a function of by time data under the vacuum. The developed calculation systems made the computed more simple and easy to implement by the LDV system.

First method is *counting peak point* on the envelope curve which is a very well know traditional method to estimation Q-factor. Second technique is *Detected peak method,* implemented as a spreadsheet to compute of the Q-factor. Third technique is able to obtain *best fitted envelope curve* using linear regression methodology to compute Q-factor. All these three techniques were based on logarithmic decrement methodology and need further development to able to use for the different devices and measuring their performance criteria.

The experiment has been done by applying a certain biasing DC voltage depending on the required state of operation. A small value of AC voltage is added to the actuation signal to provide small oscillations in the cantilever. The vibrometer laser spot is shined on the tip of the cantilever beam, and then its velocity is recorded. To obtain the free end operation state, a small value of DC voltage less than the static pull-in limit is applied as biasing voltage. The time history of the cantilever velocity in this case is shown in Figure 5.1. The natural frequency in free standing cantilevers tested in 0.966 torr vacuum and 1.36 torr are estimated as 93 and 96 kHz respectively.

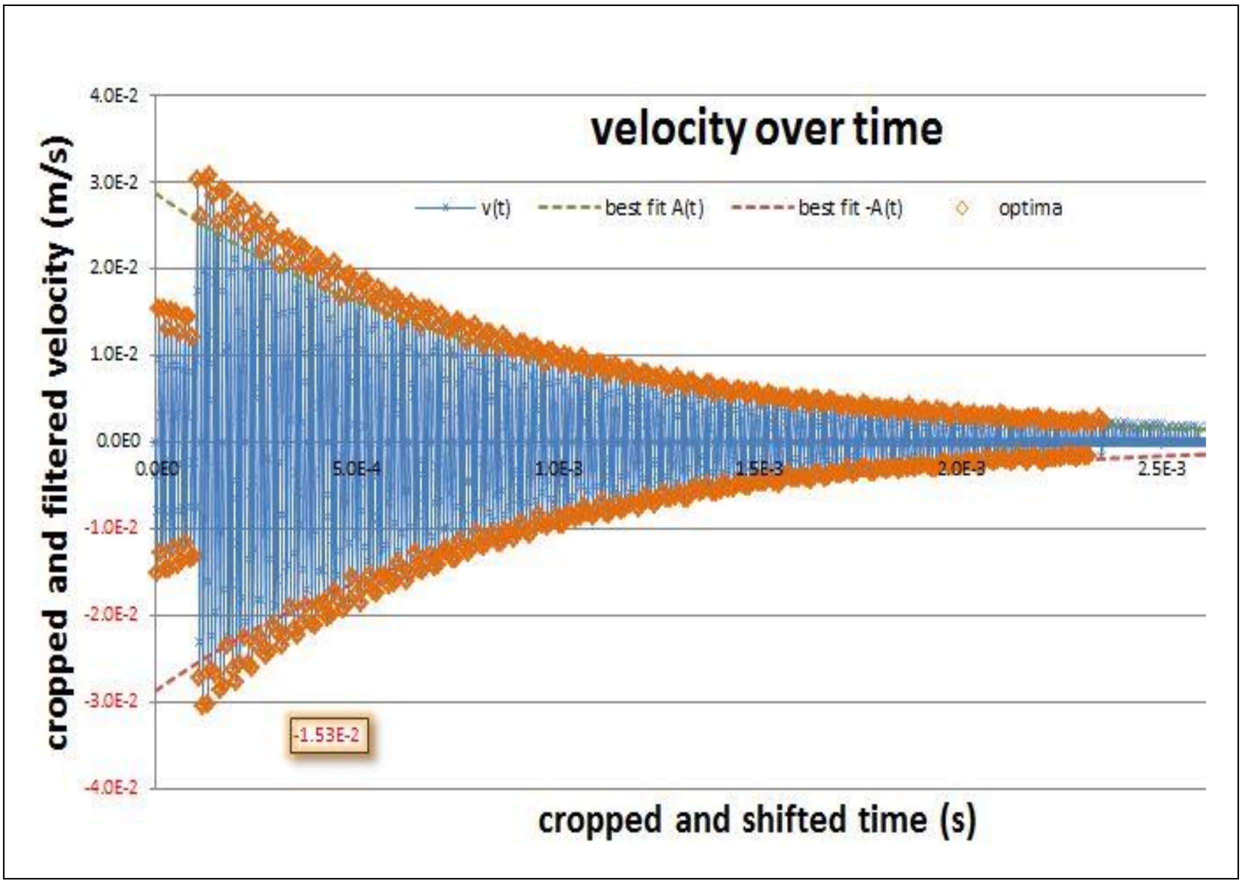


Figure 5.1 *Response of the free standing cantilever (A41-F-V-5DC-2.5Vpp-0.1 KHz)*

The actuation voltage is then increased monotonically until pull-in occurs on a line along the beam tip, line-contact. Pull-in is recognized when the velocity signal approached zero at the beam tip, while having a measurable value along the beam length. In the same manner, the time history of the cantilever velocity in the case of line contact is shown in Figure 5.2.

The natural frequency in this case is estimated as 420 kHz. Moreover, pull-in is verified optically by the formation of alternating bright and dark fringe fields on the cantilever using the vibrometer video microscope, Figure 4.3.

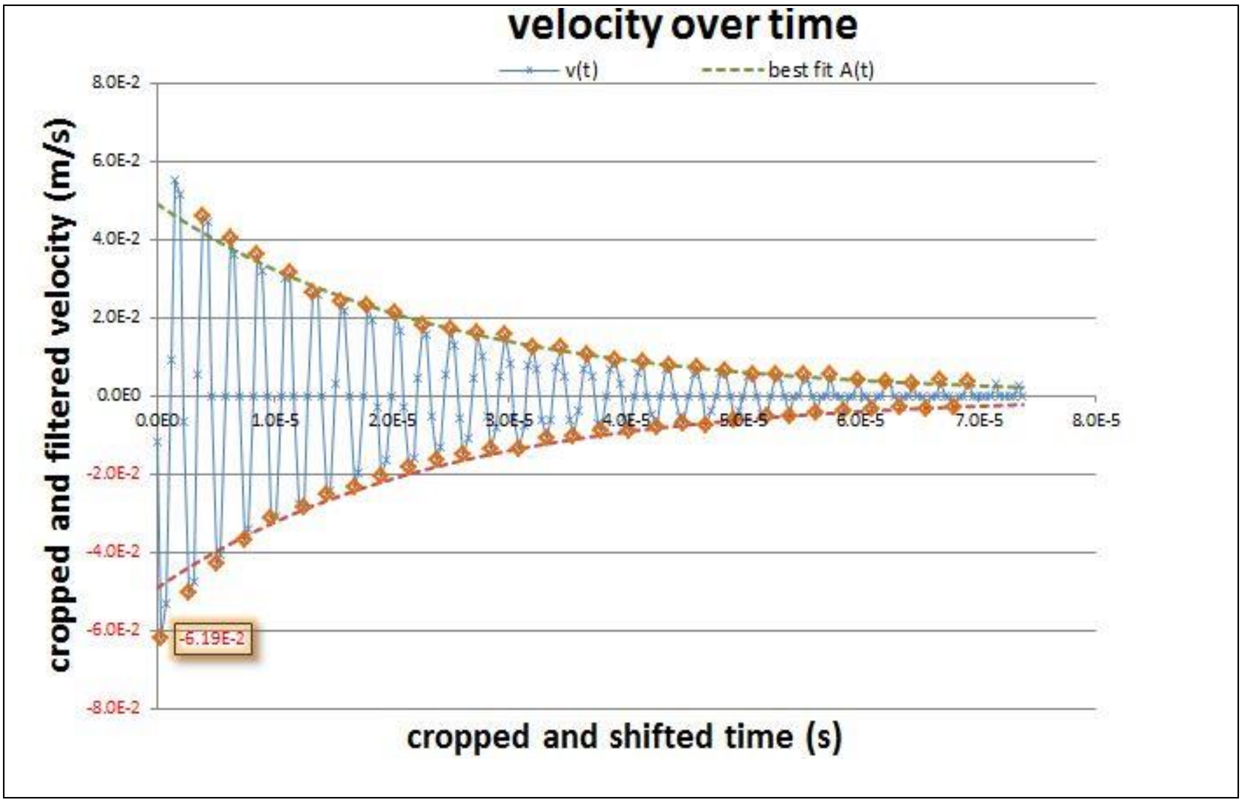


Figure 5.2 *Response of Line contact Cantilever (A12-L-V-16DC-2.5Vpp-2.5Hz)*

To achieve area-contact, biasing voltage is incrementally increased so that more area of the cantilever is in contact with the underlying ground electrode. The time history of the cantilever velocity in this case is shown in Figure 5.3 and 5.4 and the natural frequencies are estimated as 1000 and 1153 kHz for the 30% and 40% area contact cantilevers respectively.

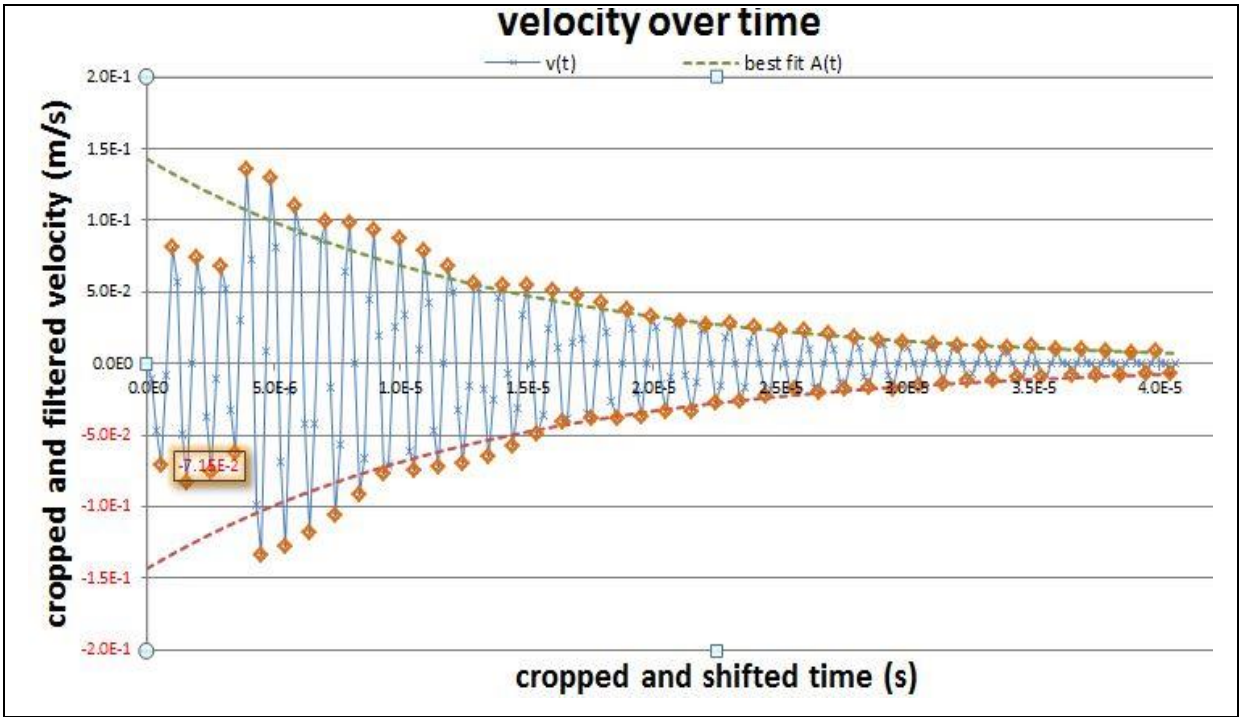


Figure 5.3 *Response of area contact cantilever (A12-A30%-V-16DC-2Vpp-2.5KHz)*

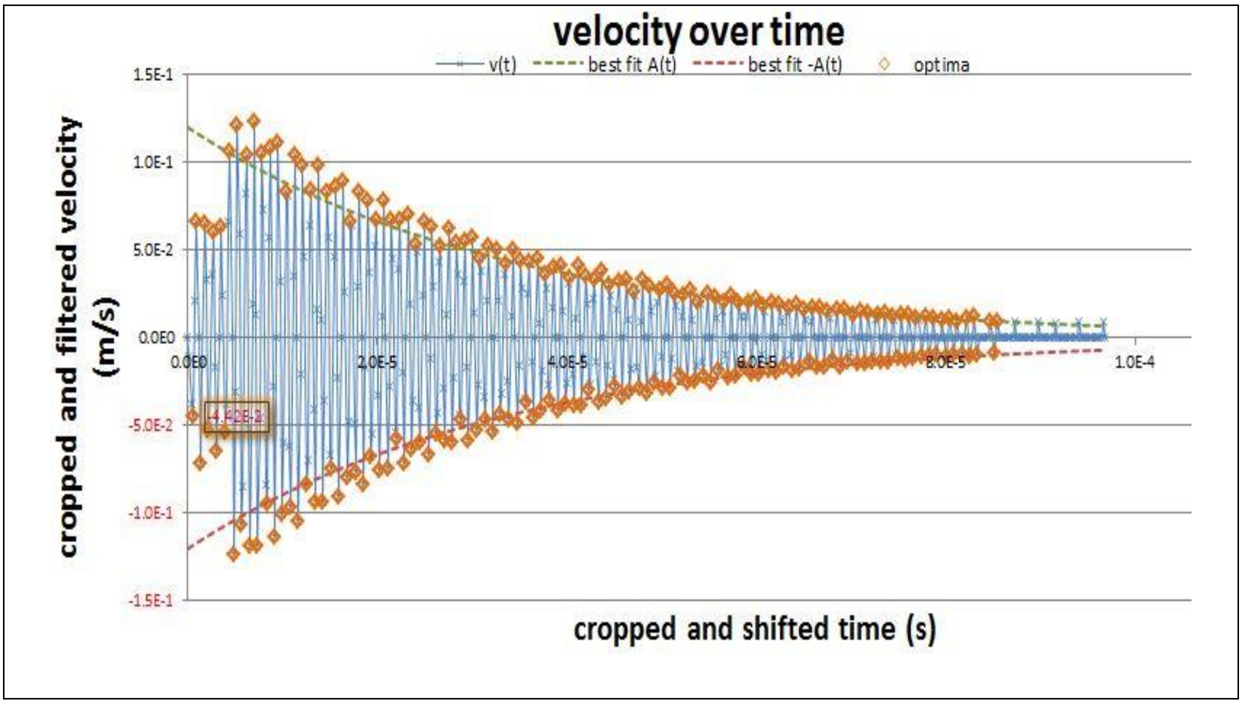


Figure 5.4 *Response of area contact cantilever (A12-A40%-V-20.5DC-2Vpp-2.5KHz.)*

Experimental measurement detailed results based on BFEF (best fit envelope function by linear regression methodology) methods shown in Table 3. Detail information about characteristic finding and computed Q-factor of the samples given as output of system are in listed on table 3.

Table 3: *Experimental measurement results based on BFEF (*) methods*

(*) based on best fit for envelope function by Linear Regression method		
Status of cantilever	**Free Standing**	**Line Contact**
Total number of data points, N:	**1777 - 1414**	**190**
Average period (s), T_d:	**1.079E-04 - 1.041E-04**	**2.37E-06**
Average frequency (Hz), f_d:	**92700 - 96110**	**4.22E+05**
Best fit quality factor, Q_f:	**317.6 - 262.9**	**3.17E+01**
Best fit initial amplitude, A_{0f}:	**0.03202 - 0.02874**	**4.91E-02**
Total number of optima:	**564 - 454**	**59**
Status of cantilever	**40% Area contact**	**30 % area Contact**
Total number of data points, N:	**497**	**209**
Average period (s), T_d:	**8.67E-07**	**9.96E-07**
Average frequency (Hz), f_d:	**1.15E+06**	**1.00E+06**
Best fit quality factor, Q_f:	**1.22E+02**	**4.30E+01**
Best fit initial amplitude, A_{0f}:	**1.20E-01**	**1.43E-01**
Total number of optima:	**198**	**81**

A comparison between the Q-factor and natural frequency of the cantilever for different actuation states are given as summary of experimental measurement results, in Table 4. According to these values, the experimental results show that Q-factor quadruples as contact evolves from line to area contact.

Table 4: *Summary of experimental measurement results of Q-factor.*

Cantilever Sample		**Resonance Frequency**		**Q-Factor**		
Status	**Description Codes**	**Exp.**	**Aver.**	**# of Peak**	**Est.**	**B.F.E.F**
F (0.966 torr)	**A41-F-V-5DC-2.5Vpp-0.1KHz**	**92.8**	**92.7**	**564**	**248**	**317**
F (1.34 torr)	**A41-F-V-5DC-2.5Vpp-0.1KHz.**	**96.1**	**96.11**	**454**	**328**	**263**
LC-3	**A12-L-V-16DC-2Vpp-2.5Hz-T**	**450**	**420**	**59**	**17.3**	**31.65**
30% AC	**A12-A30%-V-16DC-2Vpp-2.5KHz**	**1000**	**1000**	**81**	**51**	**43**
40% AC	**A12-A40%-V-20DC-2Vpp-3KHz.**	**1100**	**1153**	**198**	**103**	**122**
T:Time domain, FFT: Frequency Domain, F: free standing cantilever, LC: Line contact, AC: Area Contact, f: Res. Freq. KHz						
Est: Estimated by Q-factor detected peak point, B.F.E.F: Best fit for Envelope Function						

Chapter VI

6 Conclusions

Table 5 presents a comparison of the calculation techniques that we implemented and presented in this project. Required features are the *initial criteria* that have been defined in the beginning of study.

Table 5: *Comparison chart of calculation techniques of Q-factor (CT-Q)*

Required features of Calculation Technique of Q	#of Peak	Est.	B.F.E.F
CT-Q should be automatically calculation Q-factor of MEMS based on out-put data of laser Doppler vibrometer	4	4	4
CT-Q should be use system's output directly (no need to convert the data to use)	4	4	4
CT-Q able to integration to other measurement systems when it will be necessary	1	1	3
CT-Q can be fully benefits of traceability and accuracy of the most versatile solution	3	3	5
CT-Q can be applicable accurately both academic and industrial	3	4	5
CT-Q able to automatically reporting important data such as, resonance frequency, amplitude, graph of damping	4	4	4
# of Peak: Counting the peaks Point, Est: Detected peak points			
B.F.E.F: Best fit for Envelope Function by Linear Regression method,			

As a result, all techniques are usable for the purposes of work. Best fit for the envelope function found by linear regression method is easier to adapt for the industrial application. Both methods need improvement according to the application field. The evaluation of the methods is shown in Table 5.3. B.F.E.F method is more practical and easy to use in industrial area, in addition to giving more accurate results.

6.1 Concluding Remarks

The Q-factor was calculated using different methods for three cases: cantilever beam MEMS actuator in free standing, in line-contact, and in area-contact. Table 5.2 shows that Q-factor quadruple as contact evolved from line to area contact.

In line-contact, the cantilever was only in contact with the substrate along a line and since an AC voltage was applied which produced a dry friction effect due to the micro motion, and caused dominant dissipation on this case. This directly increased the damping in the system, and thus reduced the Q-factor.

In area-contact, there was no or very minimal micro motion, so that practically friction force was not affected, but as surface forces, van der Waals and Casimir forces were dominant forces in this case and caused light stiction effect.

The lowest value of the resonance frequency was found in line contacted cantilever, gradually rising and reaching its highest value with the sample of “40% contacted area". These findings could be due to the tensile stress application to the resonators which is well known as a powerful method for Q-factor enhancement. Verbridge et al. (2006, 2007, and 2008) has recently reported a dramatic increase in the Q-factor due to the stress application.

However, the reason of increasing the Q-factor from line to area contact could be due to the facts that cantilever has been switched from the fixed-free to fixed-fixed cantilever. As a result of this occurrence, the length of the cantilever might have got shorter and accordingly, the dimensional changes (L , A/L) affected to amplitude of vibration, gab (d), resonance frequency and the Q-factor improving due to the increasing the stiffness of beam by definition and equation of Q-factor. Thus, the resonance frequency might continuously increase from free standing to the area contact cantilever.

On the other hand, damping force is higher in line contact mode rather than area contact mode, because in line contact mode cantilever free end still moving and energy dissipation due to the friction force dominant lost. In area-contact mode, surface forces are dominant which less than friction forces are relatively. This can be another reason of describing the enhancement of Q-factor. All these possible reason of founding should be analyzed to describe enhancement of the Q-factor.

6.2 Publications

6.2.1 Journal (2014)

*"**Measuring Quality Factor for MEMS devices**"*

Austin Journal of Nanomedicine & Nanotechnology (2014)

S.Ozdemir, M.Khater, S.Akhtar, O.E.Gunal, E.Abdel-Rahman, M.Yavuz

6.2.2 Aplied Physics Letter-2014

"Contact Damping inMEMS Actuator "

M Khater, S. Akhtar, Sangtak Park, , S. Ozdemir, E. Abdel-Rahman, C.P.Vyasarayani, M. Yavuz

6.3 Future Work

6.3.1 Extension of the current thesis project:

- All these three techniques based on logarithmic decrement methodology need further development to use for different devices (especially light, optics and photonics devices).
- BFEF software must include an interface program which will automatically receive test outputs from vibrometer and calculate the Q-factor. System outputs should be received from plotter and/or printer according to needs.
- Uncertainty methodology may be integrated to the calculation system in order to get more reliable results [7]. So future studies are needed to apply uncertainty calculation due to the fact that the selected criteria depending on the experimental set-up.
- All these studies are based on logarithmic decrement method and linear regression methodology. Similar approach can be developed to calculate the Q-factor, by using the half-power bandwidth formula [27]. For this approach, non- linear regression methodology [52] will be implemented to the bandwidth curve (FFT domain) function.

6.3.2 Research topics for future works:

R&D packaging project: 3D package (System in Package, Chip Stack MCM, etc.) contains two or more IC stacked vertically so that they occupy less space and/or have greater connectivity. Through-silicon via (TSV) is a vertical electrical connection (VIA-Vertical Interconnect Access) passing completely through a silicon wafer or die [53]. This new technology needs further research to solve the issues such as BOM compatibility (bump metallurgies, passivation materials), failure issues, test methods, fabrication cost, handling and shipping [51].

Reliability of MEMS: Specifically, the reliability of the packaging and developing non-destructive test methods in general for the MEMS and Packaging will be critically important work for the researchers.

Strategic planning of the research projects: The main idea is that the research projects able to usable and applicable by the industry. That is why universities and research institutes should prepare realistic marketing review study to have "market road map document" which clearly contains market trends, motivation criteria, market and industrial demands, issues, challenges opportunities and success factors [40, 49, and 50].

System Identification Approach: "Particle swarm optimization methodology [38, 39]" is a new population based stochastic optimization technique which is used to solve non-linear, non-differentiable, multi-modal optimization problems [35]. This approach can be adapted to the Q-factor calculation system in order to verify the test results.

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