



# **ESTABLISHMENT AND CHARACTERIZATION OF REFERENCE SYSTEM FOR CALIBRATION OF DYNAMIC PRESSURE SENSORS**

By

**Shaker Abdelwahab Shaker Gelany**

A Thesis Submitted to the  
Faculty of Engineering at Cairo University  
in Partial Fulfillment of the  
Requirements for the Degree of  
**DOCTOR OF PHILOSOPHY**

in  
**MECHANICAL DESIGN AND PRODUCTION ENGINEERING**

FACULTY OF ENGINEERING, CAIRO UNIVERSITY

GIZA, EGYPT

2019

# **ESTABLISHMENT AND CHARACTERIZATION OF REFERENCE SYSTEM FOR CALIBRATION OF DYNAMIC PRESSURE SENSORS**

By

**Shaker Abdelwahab Shaker Gelany**

A Thesis Submitted to the  
Faculty of Engineering at Cairo University  
in Partial Fulfillment of the  
Requirements for the Degree of  
**DOCTOR OF PHILOSOPHY**

in

**MECHANICAL DESIGN AND PRODUCTION ENGINEERING**

**Under the Supervision of**

**Prof. Dr. Tarek Abd El Sadek Osman**

**Prof. Dr. Abdel Aziz Mahmoud**

Professor of Machine Design and Tribology  
Dept. of Mechanical Design and Production Eng.  
Faculty of Engineering, Cairo University

Professor of Mechanical Engineering  
Dept. of Mechanical Engineering  
National Research Centre

**Dr. Alaaeldin Abdelfattah Eltawil**

**Dr. Bassam Abdellatif Hussein**

Associate Professor  
Dept. Mass, Density and Pressure Metrology  
National Institute of Standards

Assistant Professor  
Dept. of Mechanical Design and Production Eng.  
Faculty of Engineering, Cairo University

FACULTY OF ENGINEERING, CAIRO UNIVERSITY

GIZA, EGYPT

2019

# **ESTABLISHMENT AND CHARACTERIZATION OF REFERENCE SYSTEM FOR CALIBRATION OF DYNAMIC PRESSURE SENSORS**

By  
**Shaker Abdelwahab Shaker Gelany**

A Thesis Submitted to the  
Faculty of Engineering at Cairo University  
in Partial Fulfillment of the  
Requirements for the Degree of  
**DOCTOR OF PHILOSOPHY**  
in  
**MECHANICAL DESIGN AND PRODUCTION ENGINEERING**

Approved by the  
Examining Committee

---

**Prof. Dr. Tarek Abd El Sadek Osman,**

**Thesis Main Advisor**

---

**Prof. Dr. Ali Ahmed Khattab,**

**Internal Examiner**

---

**Prof. Dr. Ali E. Abuelezz,**

**External Examiner**

Professor of material science and metrology - National Institute of Standards

FACULTY OF ENGINEERING, CAIRO UNIVERSITY  
GIZA, EGYPT  
2019

**Engineer:** Shaker Abdelwahab Shaker Gelany  
**Date of Birth:** 16 / 8 / 1981  
**Nationality:** Egyptian  
**E-mail:** [Shaker9595@yahoo.com](mailto:Shaker9595@yahoo.com)  
**Phone:** +201010304830



**Address:** 9 Zakaria Uonis St., Mostashfa El Haram Giza, Egypt  
**Registration Date:** 1/10/2014  
**Awarding Date:** ....../....../2019  
**Degree:** Doctor of Philosophy  
**Department:** Mechanical Design and Production  
**Supervisors:**

Prof. Dr. Tarek Abd El Sadek Osman  
Prof. Dr. Abdel Aziz Mahmoud  
Ass. Prof. Dr. Alaaeldin Abdelfattah Eltawil  
Dr. Bassam Abdellatif Hussein

**Examiners:**

Prof. Dr. Ali E. Abuelezz (External examiner)  
Professor of material science and metrology - National Institute of Standards  
Prof. Dr. Ali Ahmed Khattab (Internal examiner)  
Prof. Dr. Tarek Abd El Sadek Osman (Thesis main advisor)

**Title of Thesis:**

Establishment and characterization of reference system for calibration of dynamic pressure sensors

**Key Words:** Dynamic pressure, Falling mass, Dynamic calibration, Impulse generator

**Summary:**

Measurement standards for dynamic pressure and its traceability to the International System of Units (SI) is a novel field in metrology. Therefore, such standards are not commonly found in National Metrology Institutes (NMIs) that could enable calibration of modern dynamic pressure transducers. For several industrial fields using dynamic pressure technologies, this, in turn, limits quality assurance. Due to, the lack of traceability in the dynamic pressure measurements, the dynamic pressure sensors and transducers are calibrated using static or quasi-static methods. This may lead to significant errors in measurements as the behavior of the sensor in the dynamic mode differs from the static mode. In response to this problem, this study has been dedicated to establish and investigate a primary standard system for dynamic pressure measurements up to 100 MPa with relative uncertainty as low as 1.5 %. This new reference dynamic pressure standard is of crucial importance to develop calibration methods for dynamic pressure transducers. Furthermore, it provides the metrological basis for the dynamic pressure technologies such as automotive industries, military, aerodynamics, medicine, and material testing.

## **Disclaimer**

I hereby declare that this thesis is my own original work and that no part of it has been submitted for a degree qualification at any other university or institute.

I further declare that I have appropriately acknowledged all sources used and have cited them in the references section.

Name: Shaker Abdelwahab Shaker Gelany

Date: /6/2019

Signature:

## Acknowledgments

*First of all, praise is to ALLAH for without HIS will, this work would not have even started.*

*I wish to express my deep gratitude and respect to my supervisors committee: Prof. Dr. Tarek Osman, Prof. Dr. Abdel Aziz Mahmoud, Dr. Alaaeldin Eltawil and Dr. Bassam Abd El Atif for their guidance and support. Their helpful and valuable discussions were the core reason for accomplishing this work.*

*My thanks and gratitude are also dedicated to every member of my family and my colleagues at the NIS, Egypt, especially Dr. Abdallah Karmalawi, for their invaluable help and their patience and understanding all along the way.*

*Finally, I would like to express my boundless gratitude and sincere appreciation to **my mother** and **my father** and **beloved sister** and **brothers**. Special Thanks for my darling wife **Amany** and my kids' **Rehab, Rana, Ziad** and **Hana**.*

# Table of Contents

<b>DISCLAIMER.....</b>	<b>I</b>
<b>ACKNOWLEDGMENTS .....</b>	<b>II</b>
<b>TABLE OF CONTENTS.....</b>	<b>III</b>
<b>LIST OF TABLES .....</b>	<b>VI</b>
<b>LIST OF FIGURES .....</b>	<b>VII</b>
<b>NOMENCLATURE .....</b>	<b>IX</b>
<b>ABSTRACT .....</b>	<b>XII</b>
<b>CHAPTER 1: INTRODUCTION .....</b>	<b>1</b>
1.1. INTRODUCTION .....	1
1.2. MOTIVATION .....	1
1.3. AIM OF THE WORK.....	2
1.4. OVERVIEW OF THE THESIS .....	2
1.5. BACKGROUND .....	3
1.6. DIMENSIONS OF THE SI-UNITS OF PRESSURE.....	4
1.7. TRACEABILITY OF PRESSURE INSTRUMENTS.....	4
1.7.1. Static pressure traceability .....	5
1.7.2. Dynamic pressure traceability.....	7
1.8. PRINCIPLES OF DYNAMIC PRESSURE MEASURING INSTRUMENTS .....	13
1.8.1. Strain gauge sensing element.....	13
1.8.2. Piezoelectric pressure sensing element.....	13
1.8.3. Optical pressure sensing.....	14
1.8.4. Capacitive sensing.....	14
1.9. DIGITAL SIGNAL PROCESSING.....	15
1.9.1. Digital filters.....	15
1.9.2. FFT analysis .....	17
1.9.3. Signals coherence.....	17
<b>CHAPTER 2: LITERATURE REVIEW .....</b>	<b>18</b>
2.1. STANDARD LEVEL OF DYNAMIC PRESSURE CALIBRATION.....	18
2.2. REFERENCE LEVEL OF DYNAMIC PRESSURE CALIBRATION .....	22

## **CHAPTER 3: SYSTEM BASIC CONCEPT AND MODELING..... 24**

3.1. INTRODUCTION .....	24
3.2. BASIC CONCEPT.....	24
3.3. CALCULATION OF DYNAMIC PRESSURE DUE TO FALLING MASS .....	24
3.4. MATHEMATICAL MODELING OF THE PIEZOELECTRIC PRESSURE SENSOR .....	27
3.4.1. System identification.....	28
3.5. UNCERTAINTY ANALYSIS .....	30
3.5.1. Uncertainty using GUM method.....	30
3.5.2. Uncertainty using the MC method .....	32

## **CHAPTER 4: DESIGN AND CONSTRUCTION OF DYNAMIC PRESSURE CALIBRATION SYSTEM..... 33**

4.1. INTRODUCTION .....	33
4.2. DESIGN OBJECTIVE.....	33
4.3. MECHANISM STRUCTURE .....	34
4.3.1. Main frame .....	34
4.3.2. Mass lifter .....	36
4.3.3. Falling mass.....	38
4.4. PRESSURE TEST RIG.....	41
4.5. CONTROL UNIT .....	42
4.5.1. Microcontroller.....	42
4.5.2. Stepper motor .....	42
4.5.3. Electromagnets .....	43
4.6. MACHINE OPERATING SOFTWARE .....	44
4.7. MEASUREMENTS FACILITY .....	45
4.7.1. Velocity sensor.....	45
4.7.2. Dynamic pressure sensor.....	45
4.7.3. Accelerometer sensor .....	46
4.7.4. Charge amplifier.....	47
4.7.5. Data acquisition system.....	48

## **CHAPTER 5: EXPERIMENTAL PROCEDURE ..... 49**

5.1. SYSTEM CHARACTERIZATION PROCEDURE.....	49
---	----



5.1.1. Mass calibration .....	49
5.1.2. Calibration of the piston effective area .....	49
5.2. DYNAMIC PRESSURE CALIBRATION SEQUENCE .....	50
5.3. PROCEDURE FOR REFERENCE PRESSURE CALCULATION .....	51
5.3.1. Procedure to calculate the piston displacement .....	51
5.3.2. The falling velocity measurement .....	52
<b>CHAPTER 6: RESULTS AND DISCUSSIONS.....</b>	<b>53</b>
6.1. CHARACTERIZATION OF THE DYNAMIC PRESSURE CALIBRATION SYSTEM .....	53
6.1.1. Metrological characteristics of the dynamic calibration machine .....	53
6.1.2. Signal processing analysis .....	54
6.2. DETERMINATION OF THE REFERENCE PRESSURE .....	59
6.2.1. Measurement of the falling velocity .....	59
6.2.2. Measurement of the piston acceleration .....	60
6.2.3. Calculation of the piston displacements .....	63
6.3. VALIDATION OF THE REFERENCE PRESSURE .....	64
6.4. RESULTS OF UNCERTAINTY ANALYSIS .....	66
6.4.1. Uncertainty using GUM method .....	66
6.4.2. Uncertainty using the Monte Carlo method .....	68
6.5. RESULTS OF DYNAMIC CALIBRATION FOR A PIEZOELECTRIC PRESSURE SENSOR.....	70
6.5.1. Linearity of the sensor under calibration .....	70
6.5.2. Dynamic characteristics of the sensor under calibration .....	71
6.5.3. Dynamic sensitivity of sensor under calibration .....	72
<b>CHAPTER 7: CONCLUSION AND FUTURE WORK.....</b>	<b>73</b>
7.1. CONCLUSION.....	73
7.2. FUTURE WORK.....	74
<b>REFERENCES .....</b>	<b>75</b>
<b>APPENDIX A: PUBLICATION.....</b>	<b>78</b>
<b>APPENDIX B: WORKING DRAWINGS .....</b>	<b>83</b>

## List of Tables

Table 4-1: Mechanical properties of St 42 .....	37
Table 4-2: Material properties of the falling mass and the piston .....	39
Table 4-3: Technical specifications for Microcontroller .....	42
Table 4-4: Technical Specification of the dynamic pressure Sensors .....	46
Table 4-5: Technical specification of the accelerometer sensor .....	47
Table 4-6: Technical specification of the signal conditioner.....	47
Table 4-7: Technical specification of the digital oscilloscope .....	48
Table 6-1: Results of mass calibration .....	53
Table 6-2: NIS Local gravity acceleration .....	53
Table 6-3: Piston cylinder assembly effective area.....	53
Table 6-4: Maximum measurement values .....	65
Table 6-5: Type <i>B</i> uncertainty of dynamic pressure calibration machine .....	67
Table 6-6: Parameters for propagation distributions and estimate values .....	68
Table 6-7: Reference pressure values with expanded uncertainty .....	70
Table 6-8: The results of dynamic analysis of the pressure sensor under calibration .....	72

# List of Figures

Figure 1-1: pressure measurement modes[5] .....	3
Figure 1-2: Relation of Pa to SI base unit .....	4
Figure 1-3: Traceability chain.....	5
Figure 1-4: IMGC/CENAM-HG6 mercury manometer [8] .....	6
Figure 1-5: Schematic principle of pressure balance .....	7
Figure 1-6: Shock tube system.....	8
Figure 1-7: Step pressure sequence in shock tube [12] .....	9
Figure 1-8: Fast opening device Diagram .....	10
Figure 1-9: schematic of a free fall pulse generator .....	11
Figure 1-10: Rotating valve [15].....	11
Figure 1-11: Vibrating liquid column .....	12
Figure 1-12: Layout of the dynamic pressure measurement system.....	13
Figure 1-13: strain gauge sensing device .....	13
Figure 1-14: The transverse piezoelectric effect .....	14
Figure 1-15: Interferometer pressure sensing.....	14
Figure 1-16: Capacitive sensing .....	15
Figure 1-17: Low pass filter .....	15
Figure 1-18: High pass filter .....	16
Figure 1-19: Band pass filter .....	16
Figure 1-20: Notch filter.....	17
Figure 2-1: PTB Schematic setup of dynamic pressure system [16] .....	18
Figure 2-2: Schematic of MIKES drop weight system[17] .....	19
Figure 2-3: NPL Shock tube system[18].....	20
Figure 2-4: Shock tube stage of operation [18].....	20
Figure 2-5: KRISS Dynamic calibration system[19] .....	22
Figure 2-6: UME drop mass system up to 800 MPa[20].....	22
Figure 2-7: The schematic of the square wave pressure generator system[21] .....	23
Figure 3-1: Falling mass- Pressure test rig model .....	25
Figure 3-2: Dynamic pressure sensor model.....	27
Figure 3-3: System identification methodology .....	28
Figure 3-4: Process of the system identification method .....	29
Figure 3-5: Propagation distribution of input quantities .....	32
Figure 4-1: NIS standard dynamic calibration system .....	33
Figure 4-2: Main frame structure .....	34
Figure 4-3: Exploded view of main frame .....	35
Figure 4-4: Schematic of (a) upper plate and (b) lower plate.....	35
Figure 4-5: Schematic of frame tie rod with dimension .....	35
Figure 4-6: Mass lifter mechanism .....	36
Figure 4-7: Schematic of the mass holder with dimensions in mm.....	36
Figure 4-8: Schematic of a guide rod for falling mass .....	37
Figure 4-9: The fixation of the mass holder.....	38
Figure 4-10: FE von Mises stresses of the mass holder .....	38
Figure 4-11: Falling mass.....	39
Figure 4-12: The fixation of the falling mass and the piston.....	39

Figure 4-13: Stresses of the nonlinear contact between the mass holder and the piston.....	40
Figure 4-14: Pressure test rig with an exploded view on the right side .....	41
Figure 4-15: Concrete foundation for the pressure test rig .....	41
Figure 4-16: Arduino Uno microcontroller .....	42
Figure 4-17: Stepper motor circuit diagram .....	43
Figure 4-18: Electromagnet for lifting the falling mass .....	43
Figure 4-19: Front panel window of machine operating software.....	44
Figure 4-20: Block diagram window of machine operating software .....	44
Figure 4-21: (a) Falling velocity measuring system and (b) the output signal .....	45
Figure 4-22: Piezoelectric dynamic pressure sensor .....	46
Figure 4-23: Shock accelerometer sensor .....	47
Figure 4-24: Signal conditioner charge amplifier .....	47
Figure 4-25: Digital storage oscilloscope .....	48
Figure 5-1: Calibration using a mass comparator and standard masses .....	49
Figure 5-2: calibration of the effective area of PCA .....	50
Figure 5-3: Signals received by the oscilloscope .....	51
Figure 5-4: Piston velocity calculation sequence from the acceleration signal .....	52
Figure 5-5: Piston displacement calculation .....	52
Figure 6-1: Original Signals captured by the Oscilloscope .....	54
Figure 6-2: Original accelerometer sensor signal.....	54
Figure 6-3: Low pass filtered signal .....	55
Figure 6-4: High pass filtered accelerometer signal.....	55
Figure 6-5: FFT for low pass accelerometer signal at different loading heights .....	56
Figure 6-6: FFT analysis for the high pass accelerometer signal .....	56
Figure 6-7: Piezoelectric pressure sensor signal .....	57
Figure 6-8: High-frequency pressure signal.....	57
Figure 6-9: High pass signal FFT analysis of piezoelectric pressure sensor .....	58
Figure 6-10 Accelerometer and pressure sensors output signals .....	58
Figure 6-11: Coherence analysis at different loading condition.....	59
Figure 6-12: The traveling time of the falling mass.....	60
Figure 6-13: Measurement of the falling velocity .....	60
Figure 6-14: Acceleration- Time Curve at different falling height ( <i>a-n</i> ).....	63
Figure 6-15: Piston displacements - time curve .....	64
Figure 6-16: Piezoelectric pressure-time curve.....	65
Figure 6-17: Repeatability of dynamic pressure .....	66
Figure 6-18: Relative pressure error with uncertainty bar.....	67
Figure 6-19: PDF of falling mass.....	68
Figure 6-20: PDF of falling velocity .....	68
Figure 6-21: PDF of piston displacement .....	69
Figure 6-22: PDF of piston area.....	69
Figure 6-23: PDF of maximum pressure.....	69
Figure 6-24: Linearity of the sensor under calibration .....	70
Figure 6-25: Residual charge versus reference pressure .....	71
Figure 6-26: Measured and simulated dynamic pressure .....	71
Figure 6-27: Dynamic sensitivity of sensor under calibration.....	72

# Nomenclature

$p$	Pressure, Pa
$p(t)$	Pressure function of time, Pa
$h$	Height of the liquid column, m
$p_r$	Reference pressure, Pa
$g$	Gravitational acceleration, m/s <sup>2</sup>
$m$	Mass, kg
$A_p$	Effective area, m <sup>2</sup>
$M_1$	Mach number of the shock wave
$f_c$	Cutoff frequency, Hz
$f_H$	Cutoff high-frequency, Hz
$f_L$	Cutoff low frequency, Hz
$m_{tot}$	The total mass of piston, drop weight and fluid mass, kg
$\ddot{x}_{max}$	The maximum acceleration, ms <sup>-2</sup>
$P_S$	Pressure reservoir, Pa
$W_{net}$	work done, J
$F$	Force, N
$x_{max}$	Maximum piston displacement, m
$m_f$	Falling mass, kg
$m_p$	Piston mass, kg
$v_0$	Initial velocity, m/s
$v$	The resultant velocity, m/s
$V(t)$	Piston velocity, m/s
$k$	Stiffness, N.m
$c$	Viscous damping coefficient, N.s/m
$K$	Dynamic sensitivity, pC/MPa

$n$	Number of observations
$\bar{x}$	Mean of observations
$N$	Number of components
$d$	The width of the edge, m
$t$	The traveled time, sec

## Greek nomenclature

$\alpha_1$	The speed of sound in shock tube, m/s
$\gamma_1$	The gas specific heat ratio in shock tube
$\Delta p$	The pressure difference between the two chambers, Pa
$\omega_d$	Damped frequency, rad/s
$\omega_n$	Natural frequency, rad/s
$\xi$	Damping ratio
$\rho_f$	Fluid density, $\text{kgm}^{-3}$
$\rho_a$	the air density, $\text{kgm}^{-3}$
$\rho_m$	The mass density, $\text{kgm}^{-3}$
$\gamma$	The surface tension of the test piston oil, N
$C$	The circumference of the test piston, m
$\alpha_p$	The thermal expansion coefficients of the piston material, $^{\circ}\text{C}^{-1}$
$\alpha_c$	The thermal expansion coefficients of the cylinder material, $^{\circ}\text{C}^{-1}$
$\sigma$	The standard deviation

## Abbreviations

SI	International System of units
NMIs	National Metrology Institutes
FEM	Finite Element Method
NIS	National Institute of Standards, Egypt
FFT	Fast Fourier Transform
DFT	Discrete Fourier Transform
PTB	Physikalisch-Technische Bundesanstalt, Germany
VTT	Technical Research Centre, Finland
MIKES	Centre for Metrology, Finland
NPL	National Physical Laboratory, UK
KRISS	Korea Research Institute of Standards and Science
UME	National Metrology Institute, Turkey
PTFE	Polytetrafluoroethylene
GUM	Guide of Uncertainty in Measurement
MC	Mount Carlo
PDF	Probability Density Functions
DAQ	Data Acquisition system
RS	Reference Sensor
UC	Under Calibration