Design of Non-contact Transduction Based Pressure Sensor using Tunneling Magnetoresistive (TMR) Principle

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***Abstract*— A pressure sensor with non-contact transduction which measures deflection of diaphragm due to applied pressure, using tunneling magnetoresistive (TMR) principle is aimed to meet the requirements of pressure measurement in harsh environments. In commonly used strain gauge type of pressure sensor, strain depends not only on pressure but also on media temperature which induces more error or burnout strain gauges at high temperature. A novel non-contact measurement principle to detect diaphragm deflection is proposed that allows to overcome these limitations. For this purpose, Samarium Cobalt magnet and TMR sensor are used. As transduction is non-contact, this method is useful to measure pressure of hot gas produced by combustion of short duration. This paper presents the design of pressure sensor using TMR principle and its evaluation supported by the simulated test results. Further scope of work towards improvement of accuracy and confidence on pressure measurement has been concluded to aid sensor design in future.**

***Index Terms*— Aerospace application, diaphragm, non-contact transduction, TMR sensor, calibration .**

I. INTRODUCTION

In general, applied pressure is measured by detecting either deflection of diaphragm or induced stress in the diaphragm [1]. In Aerospace applications, most often pressure sensor uses piezoresistive technique as transduction mechanism from pressure to change in resistance [2]. Strain gauges are used for this purpose. Thin film strain gauges with a metal diaphragm suffers due to low sensitivity and thermal error [3]. The most significant limitation of strain gauge is the susceptibility to electromagnetic interferences [4].

Acquiring transient pressure of combustion chamber during static testing of aerospace vehicle for its performance evaluation is challenging due to the limitations of service temperature and temperature co efficient of strain gauges. The highly dynamic and static pressure can be measured using two transduction elements namely piezoelectric crystal and platinum thin film strain gauges positioned on a single diaphragm [5]. The static test environment is harsh, typically contains transient pressure developed by high temperature gases [2,6] which forces strain gauges beyond its operating temperature and induces thermal error. Correction algorithm may be employed for temperature compensation to improve the accuracy of pressure measurement in harsh environment [7] .

An alternate solution to measure pressure in harsh environment, is using transduction mechanism other than strain gauges. Displacement sensing principle [8-10] may be employed for improvement in pressure measurement. The method of achieving parts per million (ppm) accuracy on position measurement using MEMS (Micro Electro Mechanical Systems) based piezoresistive micro sensor is demonstrated in [11].Measurement error related to high temperature depends mainly on strain gauges [12] and contact transduction method. This forces non-contact transduction to ratify the high temperature problems using principles like optical, capacitive, inductive and magnetic [13-15]. Magnetic field detecting sensors assists measurement of force, pressure and displacement [16].

In this paper , conceptual design of an innovative non-contact transduction pressure sensor using tunneling magnetoresistive (TMR) principle is presented with simulated test results. It involves selection of materials, sensing methods, magnet, TMR sensor and thermal insulation layer. The proposed pressure sensor design includes finalization of dimensions of diaphragm, magnet and insulation layer in addition to optimization of position of TMR sensor. The performance of the designed sensor is evaluated through static calibration. Piecewise linearization technique is implemented to improve the accuracy of measured pressure.

II. PROPOSED NON-CONTACT TRANSDUCTION BASED PRESSURE SENSOR

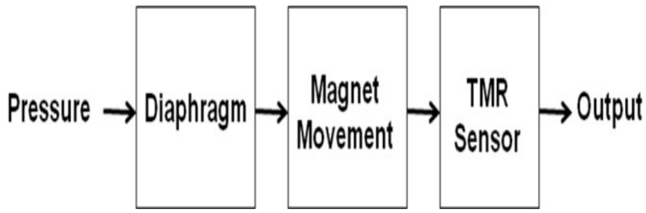

Fig. 1. Block diagram of non-contact transduction pressure sensor

The proposed non-contact transduction scheme for pressure measurement is shown in Fig.1. In this scheme, a magnetic film is deposited on the metallic diaphragm and a TMR sensor is positioned on the central axis of the diaphragm at few millimeters above magnetic film. On application of pressure, diaphragm deflects and magnet moves up which increases field strength at TMR sensor location. TMR sensor produces output voltage proportional to field strength based on its sensitivity. The relationship between applied pressure and output voltage can be used for pressure measurement.

III. DESIGN ASPECTS OF SENSING DIAPHRAGM

Square or rectangular diaphragm produces more induced stress and less deflection compared to circular diaphragm for a given pressure [17]. Since non-contact transduction senses only displacement not induced stress, a circular diaphragm is selected.

In aerospace applications, 17- 4 PH steel plays a vital role in the design of pressure sensor diaphragm as it provides an outstanding combination of high strength, good corrosion resistance and good mechanical properties at temperatures up to 316 ºC [18]. Hence 17- 4 PH steel is selected as diaphragm material.

For convenience, diaphragm diameter is selected as 60 mm. Thickness of the diaphragm corresponding to selected diameter against rated pressure can be determined from analytical solution or Finite Element analysis(FEA)method. Equations 1, 2 and 3 aid the design of circular diaphragm against the rated pressure in case of small deflection by analytical solution [19].

$$t = \sqrt{\frac{0.75PR_0^2\left(1-\nu^2\right)}{e_0 E}} \qquad (1)$$

$$D_{\max} = \frac{3PR_0^4\left(1-\nu^2\right)}{16t^3E} \qquad (2)$$

$$f_n = \frac{0.469t}{R_0^2}\sqrt{\frac{E}{\rho\left(1-\nu^2\right)}} \qquad (3)$$

t - Thickness of diaphragm (m)
D_{max} - Center deflection (m)
f_n - Natural frequency of diaphragm
P - Rated Pressure (Pa)
R_0 - Radius (m)
ν - Poisson's ratio
E - Modulus of elasticity (Pa)
P - Mass density (kg/m^3)
e_o - Sensitivity (mV/V)

FEA is carried out using ANSYS software version 17.1 and thickness of the diaphragm is finalized as 2.5 mm.

IV. DESIGN OF NON-CONTACT TRANSDUCTION ELEMENTS

The selected non-contact transduction system contains a thin layer of permanent magnet and a magnetic sensor to detect the deflection of diaphragm proportional to the applied pressure. The strength and limitations of different types of magnet [20] like volume of magnetization (B_r), service temperature (T_S) and demagnetization resistance (H_C) are tabulated in Table I.

From Table I , Samarium Cobalt (Sm Co) magnet is considered as it has good volume of magnetization and demagnetization resistance with operating temperature up to 350ºC. Since, Sm Co 26 is the most commonly used magnet in aerospace applications, it is selected as a source for non-contact transduction.

TABLE I. PROPERTIES OF DIFFERENT TYPES OF MAGNETS

Magnet material	B_r (mT)	Density (kg/m^3)	T_S (º C)	H_C (mT)
Ne	13000	7400	80	1150
SmCo	1100	8400	350	970
Alnico	1250	7300	500	64
Ferrite	385	5000	180	295

Circular shape thin magnetic film is selected as it is easier to fabricate and provides better central line Gauss compared to that of rectangular shape [21]. Dimensions of the magnet are concluded as diameter 2mm and thickness 0.1mm from Table V.

From [22], various types of magnetic sensors like Hall effect (Hall), Anisotropic Magnetoresistive (AMR),Giant Magnetoresistive(GMR) and Tunneling Magnetoresistive (TMR) sensors with critical specifications are displayed in Table II.

From Table II, TMR sensor exhibits higher sensitivity and better resolution with operating temperatures up to 200ºC. Hence, TMR is considered for transduction. From Table VI, TMR 2303 is selected [23].

TABLE II. COMPARISON OF MAGNETIC FIELD SENSING SENSORS

Parameter	Hall	AMR	GMR	TMR
Sensitivity (mV/V/mT)	0.5	10	30	1000
Resolution (nT)	>100	0.1-10	1-10	0.1-10
Dynamic Range (mT)	900	1	10	100
T_S (° C)	<1500	<150	<150	<200
Power (mA)	20	10	10	0.01

V. TEST RESULTS AND DISCUSSIONS

Non-contact transduction is an effective solution for measurement of transient pressure developed by hot gas during static testing of aero engines , rather than preventing diaphragm temperature below compensated or operated temperature which leads to reduction of bandwidth and accuracy of the measurement chain.

In the designed pressure sensor as shown in Fig.1, diaphragm acts as primary sensing element and magnet plus magnetic field sensor act as transduction elements. Design of diaphragm related to material and shape were discussed. Finite element analysis (FEA) provides more accurate results than analytical solution for diaphragm design [24] . Hence, FEA is used for the diaphragm design and analysis. Diaphragm dimensions are finalized from the results of FEA using ANSYS software version 17.1 and input parameters mentioned in Table III . The maximum deflection(D_{max}) and maximum stress(σ_{max}) developed on the diaphragm at rated pressure and safe overload pressure for different thicknesses of diaphragm with diameter 60mm are displayed in Table IV. From the simulation results, thickness of the diaphragm is concluded as 2.5mm. In this case , natural frequency of the diaphragm (f_n) is calculated by the ANSYS is 6704 Hz.

TABLE III. DIAPHRAGM DESIGN INPUT PARAMETERS FOR FEA

Diaphragm Design input parameters for FEA	Engineering Value
Material	17-4 PH
Diameter	$60x10^{-3}$m
Young's Modulus	$197x\ 10^9$ Pa
Density	7780 kg/m^3
Poisson's ratio	0.272
Rated Pressure	6894760 Pa
Safety Factor	1.5

TABLE IV. STRESS AND DEFLECTION FOR DIFFERENT THICKNESS OF DIAPHRAGM OF SAME DIAMETER

Diaphragm thickness mm	Pressure @ 6.89 MPa		Pressure @ 10.34 MPa	
	D_{max} mm	σ_{max} MPa	D_{max} mm	σ_{max} MPa
1.0	3.28	2686	4.92	4030
1.5	1.46	1320	2.19	1980
2.0	0.611	1026	0.917	1540
2.5	0.322	657	0.483	985
3.0	0.185	469	0.278	703

The maximum yield strength of 17-4 PH steel sheet and strip in thickness from 0.38 mm to 3.18 mm with solution treated at 1038ºC±14ºC and air cool below 32ºC is 1000 MPa. As a practice, design is always aimed for safe overload pressure rather than rated pressure due to safety and reusability of sensor without correction due to permanent deformation of diaphragm. The maximum stress experienced by the diaphragm shall not exceed yield strength even at safe over load pressure. From Table IV, maximum stress experienced by the diaphragm for thickness 2.5 mm is within the yield strength and provides better deflection. Hence, diaphragm thickness is selected as 2.5mm. Figure 2 and 3 explore the deflection and stress profile of designed diaphragm i.e. diameter 60mm and thickness 2.5mm at safe over load pressure.

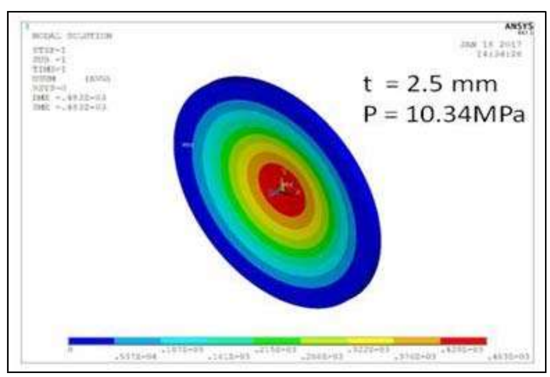

Fig. 2. Deflection Profile at safe over load pressure

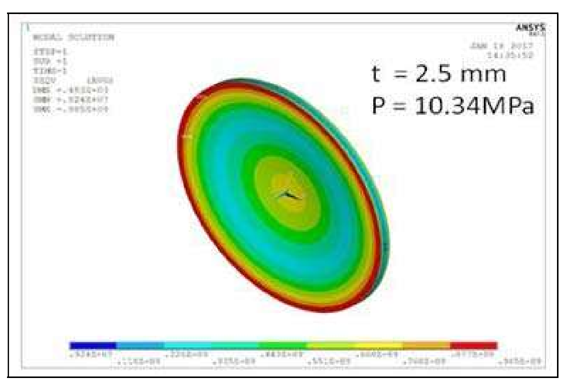

Fig. 3. Stress profile at safe overload

The characteristics of various types of magnetic materials and different shapes have been discussed. Circular thin film Samarium Cobalt (Sm Co 26) is selected due to its merits over other magnets. The magnetic field strength of the magnet with different dimensions can be calculated using Equation 4 or using central line Gauss calculation software developed by ADAMS [21].

$$B_Z = \frac{B_r}{2}\left[\frac{t+Z}{\sqrt{R^2+(t+Z)^2}} - \frac{Z}{\sqrt{R^2+Z^2}}\right] \quad (4)$$

B - Volume of magnetization (T)
B_Z - Field strength at a distance Z (T)
R - Radius of magnet (m)
t - Thickness of magnet(m)
Z - Distance from pole face of magnet (m)

Field strength at various distance pertaining to different dimensions of the selected magnet are simulated using ADAMS software and results are reported in Table V .

TABLE V. VARIATION OF FIELD STRENGTH VERSUS DISTANCE OF A MAGNET OF DIFFERENT SIZES

Diameter (D) mm	Thick ness (t) mm	Field Strength B_z from magnet surface at a distance (mT)		
		0 mm	1mm	2mm
5	0.1	19	14.3	8.3
	0.2	37.4	26.7	15.2
	0.3	54.8	37.3	21.0
3	0.1	31.4	15.9	5.9
2	0.1	46.3	13.5	3.5

Table V shows that center line Gauss (B_z) of a magnet can be increased either by increasing thickness or by reducing diameter of the magnet. Smaller diameter is preferred as it has less weight compared to that of thicker magnet. Hence, Sm Co 26 thin film magnet of diameter 2mm and thickness 0.1mm is concluded as a source for detection of diaphragm deflection about 0.483 mm at safe over load pressure. According to inverse cube law, magnetic field strength of a magnet varies inversely proportional to the cube of the distance from the magnet as highlighted in Fig.4.

Various types of magnetic field detecting sensors are analyzed and TMR sensor is selected due to its better linearity(±1%FS), resolution (0.1nT) and service temperature up to 200ºC. The characteristics of few TMR sensors available in the market are recorded in Table VI.

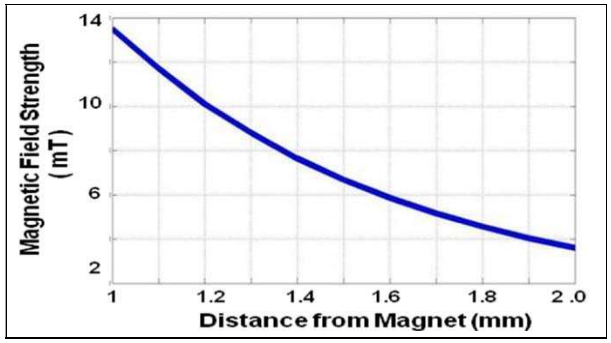

Fig. 4. Variation of magnetic field Vs Distance

TABLE VI. CHARACTERISTICS OF TMR SENSORS

Parameter	TMR Sensor		
	2303	2009	2301
Sensitivity (mV/V/mT)	30	3	10
Dynamic Range (mT)	±15	±20	±50
Non- linearity % FS	±1.5	±1.2	±1.5
Sensing Direction	X/Y/Z	X	X/Y/Z

TMR sensor 2303 is selected from Table VI , as it provides better sensitivity with dynamic range ±15 mT. Hence, magnetic field strength on TMR sensor can not exceed 15 mT under safe load pressure condition. From Tables III and IV, maximum deflection of diaphragm under safe load pressure is 0.483mm and the magnetic field at 1mm from the selected magnet surface is 13.5 mT. Hence, the position of TMR sensor from the magnet surface under no load condition is concluded as 1.5 mm.

As the magnet looses its magnetic field at temperatures above service temperature, an insulation Teflon layer of diameter 5 mm and thickness 10 microns is introduced between diaphragm and magnet. The details of various elements of designed pressure sensor are highlighted in Table VII.

TABLE VII. DETAILS OF ELEMENTS OF PROPOSED DESIGN OF NON-CONTACT TRANSDUCTION PRESSURE SENSOR

Elements	Material	Diameter mm	Thickness mm
Diaphragm	17-4 PH steel	60	2.5
Magnet	Sm Co 26	2	0.1
Insulation	Teflon	5	0.01
TMR Sensor	TMR2303 at 1.5 mm from magnet surface under no load		

AD 586T provides 5V ± 7.5 mV / 10mA from the input voltage 12-15V with service temperature from -55ºC to +125ºC, where as TMR sensor requires less than 1mA at 5V. So AD 586T is included in conditioner design to overcome the problems due to ratiometric output of TMR sensor. Instrumentation amplifier of gain 5 with offset correction configuration using AD 522 is considered to nullify the sensor output under no load and enhance the output signal to high level which is suitable for transmission.

Static calibration of designed pressure sensor is carried out by applying simulated loads in onward direction to estimate non-linearity of sensor. The calibration results corresponding to different loads are simulated using transformation of transduction and reported in Table VIII.

TABLE VIII. STATIC CALIBRATION TEST DATA

Pressure kPa	Deflection - D_{max} µm	Field Strength- B_z mT	Output V
0	0	6.68	0
689.5	32.2	6.975	0.220
1379	64.4	7.285	0.455
2068	96.6	7.611	0.700
2758	128.8	7.954	0.955
3447	161	8.317	1.225
4136	193.2	8.699	1.515
4826	225.4	9.101	1.815
5516	257.6	9.526	2.135
6205	289.8	9.974	2.470
6895	322	10.446	2.82

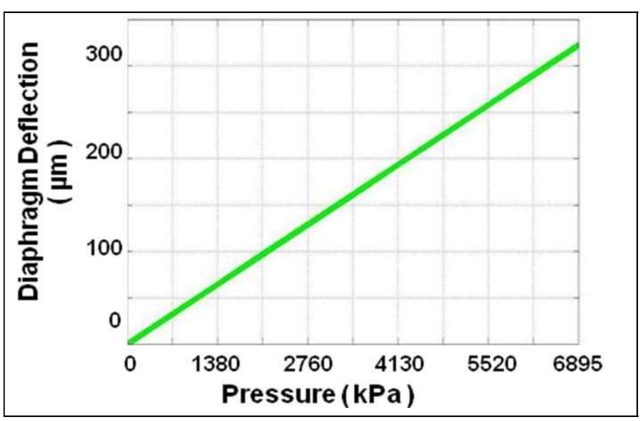

Fig. 5. Deflection Profile Vs. Pressure

From Fig.5, deflection curve is linear and calibration curve shown in Fig.6 is non-linear. From the calibration data, non-linearity is calculated as ± 4% FS. Piecewise linearisation technique [25] is employed on sensor output data using best fit straight line method (BFSL) to minimise the non-linearity error. The results obtained from linearisation are recorded in Table IX.

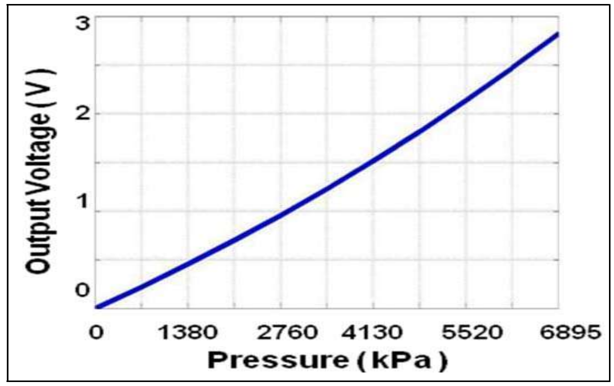

Fig. 6. Calibration curve of designed sensor

TABLE IX. LINEARIZATION RESULTS

Applied Pressure (kPa)	Sensor Output (mV)	BFSL y = mx+c		Measured Pressure Using BFSL (kPa)
		m	c	
0	0	3.1337	-2	-2
345	109			340
690	220			687
1034	335	2.9647	+40.6	1034
1379	453			1384
1724	574	2.8269	+106	1729
2068	697			2076
2413	824	2.6889	+211	2427
2758	955			2779
3103	1089	2.551	+345	3123
3447	1227			3475
3792	1368	2.4132	+516	3817
4136	1513			4167
4482	1662	2.2753	+696	4477
4826	1815			4825
5171	1972	2.1374	+912	5126
5516	2133			5470
5861	2300	2.0684	+1045	5803
6205	2470			6154
6550	2645	1.9305	+1409	6516
6895	2824			6861

From the measured pressure data in Table IX, it is prominent that linearisation has improved the accuracy of pressure measurement. The accuracy of measured pressure is calculated as ± 0.85 % FS by assuming that other elements of measurement chain will not contribute any inaccuracies.

VI. CONCLUSIONS

In this paper, the constraints imposed on strain gauge type of pressure sensor, used for measurement of transient pressure, generated by high temperature gas as a result of combustion and need aspects of non contact transduction mechanism are discussed. Design aspects of pressure sensing diaphragm with respect to material , shape and dimensions have been presented. Selection of magnet with dimensions and magnetic field measuring sensor to meet the requirement have been finalized through analysis of simulation test results. An innovative method of non-contact transduction with magnet and TMR sensor, has been conceptually designed to overcome the pressure measurement accuracy problem under the influence of high temperature without compromising bandwidth. Since the weight of magnet (2.638 mg) is negligible compared to the weight of diaphragm (55.107g), magnet is not considered for deflection calculation against the applied pressure. As the combustion duration is very less in the order of few seconds, teflon layer serves the purpose. From the calibration data, sensor output voltage varies non linearly with the applied pressure. Hence, piecewise linearization technique is used to measure pressure accurately with the designed sensor. However, sensor output is still non- linear because linearization is carried out on sensor output data at Data Acquisition Terminal. Deploying suitable linearization circuit at sensor may help in improving accuracy of the sensor. As magnet looses its power when it is exposed to high temperature, the designed sensor requires recalibration after every high temperature exposure. Self temperature compensated magnet can be used to avoid frequent recalibration requirement.

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