Proceedings

Dynamic Mechanical Simulation of Miniature Silicon Membrane during Air Blast for Pressure Measurement †

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Abstract: The development of new ultra-fast sensors for pressure air blast monitoring requires taking into account the very short rise time of pressure occurring during explosion. Simulations show here that the dynamic mechanical behavior of membrane-based sensors depends significantly on this rise time when the fundamental mechanical resonant frequency of the membrane is higher than 10 MHz.

Keywords: air blast; pressure sensor; dynamic behavior; silicon membrane

1. Introduction

The real time and dynamic measurements of pressure during air blasts is very challenging due to the abrupt variation of pressure from the atmospheric pressure to the so-called overpressure peak P_{max} (between few bars and several ten of bars) with very short rise time t_m (<100 ns) (Figure 1). For accurate measurement of P_{max}, sensors with high fundamental mechanical resonant frequency F_o are then required [1].

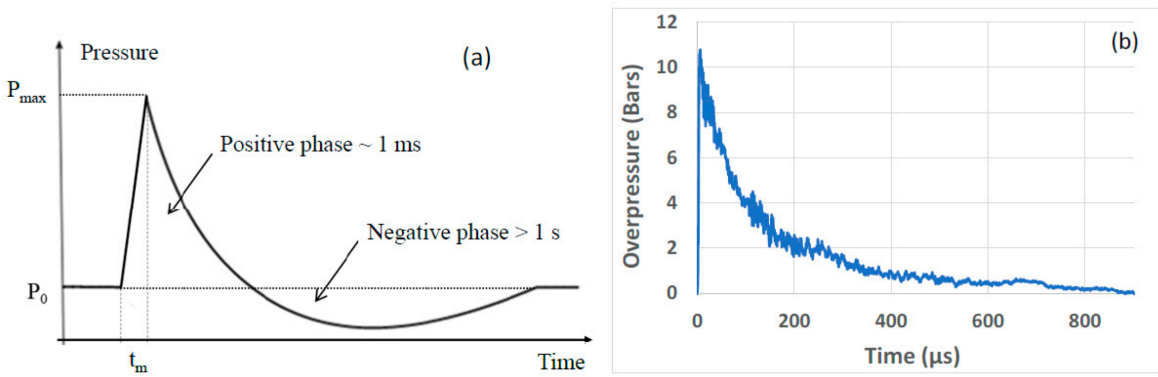

Figure 1. Typical dynamic pressure variation during an air blast experiment: (**a**) Illustration of the different phases and (**b**) example of pressure measurement at 1m from 1kgTNT by using a Tourmaline piezoelectric sensor.

When simulating a pressure sensor for which F_o << 1/tm, the rise-time is assumed to be close to zero. However, we show here that this assumption is no more valid when performing the mechanical simulation of a sensor for which F_o > 10 MHz.

2. Sensor Description and Simulation Conditions

As shown in Figure 2, the proposed sensor is based on a miniature rectangular silicon membrane (5 µm × 30 µm × 90 µm) with four piezoresistive gauges located at its center [1].

Simulations were performed using Abaqus software [2] for real membrane clamping conditions. Considering the gauges dimensions, the stresses in the gauge areas are close to ones calculated at the membrane center (error lower than 7% on the sensor response). Dynamic behavior of the sensor is then modelled by the differential stress $\Delta\sigma$ given by Equation (1) at the center of the membrane, and normalized by the static pressure:

$$\Delta\sigma = \sigma_l - \sigma_t \tag{1}$$

where σ_l (resp., σ_t) is the stress applied to the gauge parallel (resp., to the gauge perpendicular) to the current in the gauge.

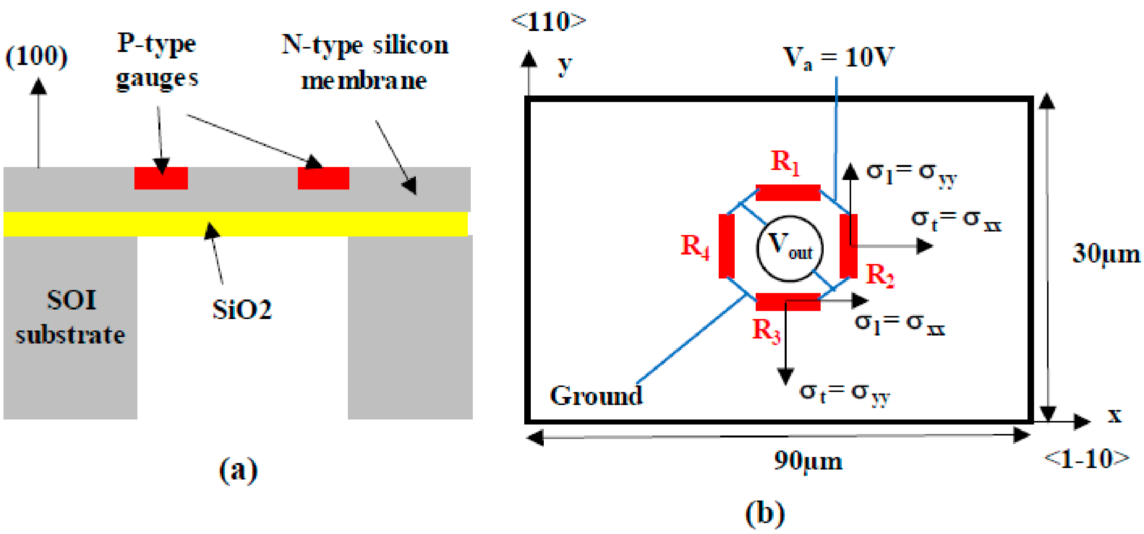

Figure 2. (**a**) Cross sectional view of the sensor; (**b**) Wheatstone bridge on the rectangular membrane.

The fundamental mechanical resonant frequency F_o, obtained from harmonic module of Abaqus software, is of 32.7 MHz and consequently 1/F_o is close to 30 ns.

Due to the short reaction time t_r of the sensor (<few µs, see Figure 5), we assume here that the pressure profile (shown on Figure 1) can be modelled by the Heaviside step function (the decrease of pressure is lower than 2% after 1 µs).

Moreover, assuming that the acoustic damping is predominant [3], the quality factor *Q* of the membrane is inversely related to the equivalent pressure P_e applied on both sides of the membrane as shown in Equation (2).

$$Q \cong \frac{95}{P_e\ (bar)} \tag{2}$$

Abaqus simulations indicates that the pressure P_e is the average pressure applied between the two membrane sides. Table 1 reports the *Q* factor for typical applied pressure on one side of the membrane while the other side is in vacuum. We observe that the *Q* factor decreases rapidly and is lower than 20 for the applied pressure greater than 10 bars.

Table 1. Q factor versus absolute pressure from Equation (2).

Pressure (Bar)	2	5	10	20	30	40
Q	95	38	19	9.5	6.3	4.8

For a shock wavefront normally incident upon the membrane surface, the dynamic mechanical response to a linear variation of pressure was obtained from the Second Order Transfer Function (SOTF) where the rise time differs from zero (Equation (3)). This model is consistent with Abaqus simulations results, as it can be noticed from Figure 3. We can observe that the difference is lower than 4% after the rise time. Consequently, the effects on sensor reaction time can be neglected.

$$\begin{aligned} \mathrm{R}_n(t) = \frac{1}{t_m} \Big\{ & t - 2.B + e^{-A.t}\left[2.B.\cos(\Omega.t) + \frac{2.\xi^2 - 1}{\Omega}\sin(\Omega.t)\right] \\ & - U(t - t_m)\Big[t - t_m - 2.B.e^{-A(t-t_m)}.(2.B.\cos(\Omega(t - t_m)) \\ & + \frac{2.\xi^2 - 1}{\Omega} sin(\Omega(t - t_m))\Big]\Big\} \end{aligned} \tag{3}$$

where ξ is the damping factor, $\mathrm{A} = \xi.\omega_o$, $\mathrm{B} = \frac{\xi}{\omega_o}$, $\Omega = \omega_o\sqrt{1 - \xi^2}$, $\omega_o = 1/F_o$.
and $U(t) = 0$, if $t < 0$, $U(t) = \frac{t}{t_m}$, if $0 < t < t_m$, $U(t) = 1$ if $t > t_m$.

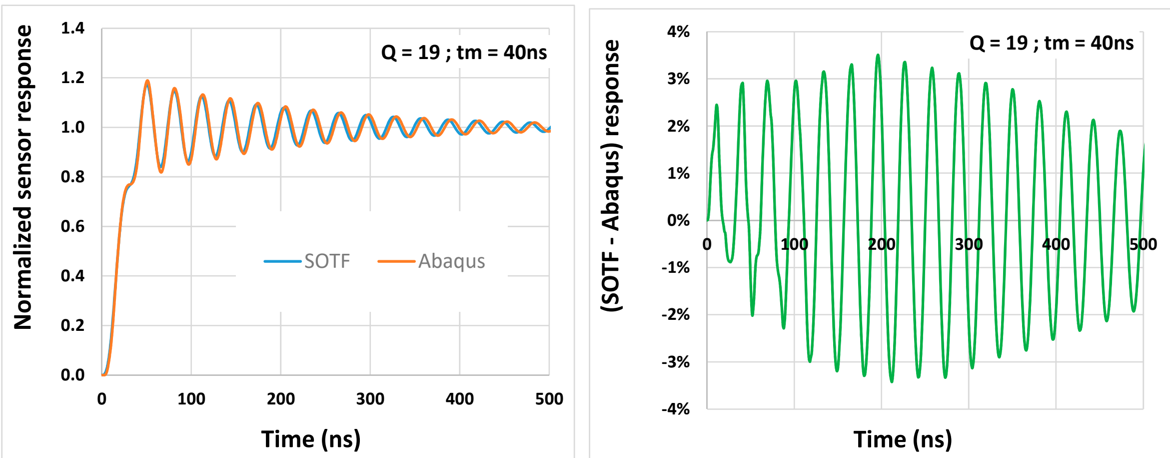

Figure 3. Comparison of SOTF model and Abaqus simulation results for the dynamic response.

3. Results

Figure 4 displays an example of the dynamic mechanical response of the membrane for rise time t_m up to 100 ns and for a *Q* factor of 19. The response is normalized by the static value. The reaction time t_r of the sensor (00B15% of the static response) is extracted from these figures for *Q* factor between 5 and 100 (Figure 5). The following observations can be made:

i. for $t_m < 1/F_o$, we retrieve the classical damped oscillation for which t_r is mainly driven by the *Q* factor ($t_r \cong Q/F_o$);
ii. as t_m increases, the reaction time tr decreases and, due to the decreasing of the fundamental mode amplitude (Figure 6), we obtain $t_r \cong t_m$ when $t_m = 1/F_o$;
iii. when $t_m = n/F_o$ where *n* is a natural number, no oscillation occurs and t_r is close to t_m;
iv. when $t_m > 1/F_o$, small oscillations appear during the rise time.

The reduction of the reaction time related to the increase of the rise time is given in Figure 7 (reaction time for $t_m = 0$ is taken as reference). We can observe that for pressure rise time tm greater than 20 ns, the sensor reaction time may be underestimated almost by 20% compared with the zero pressure rise- time ($t_m = 0$) assumption. This error may reach 100% when tm is close to n/F_o.

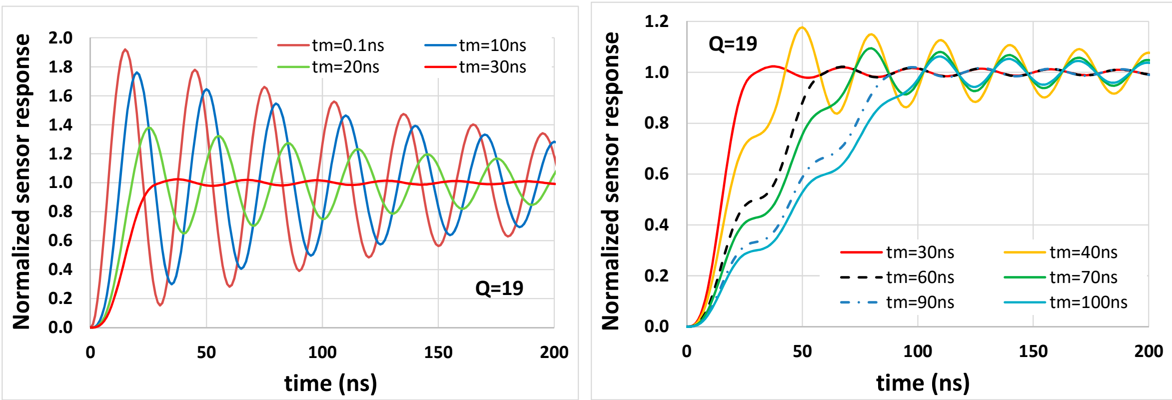

Figure 4. Dynamic sensor response for different rise times.

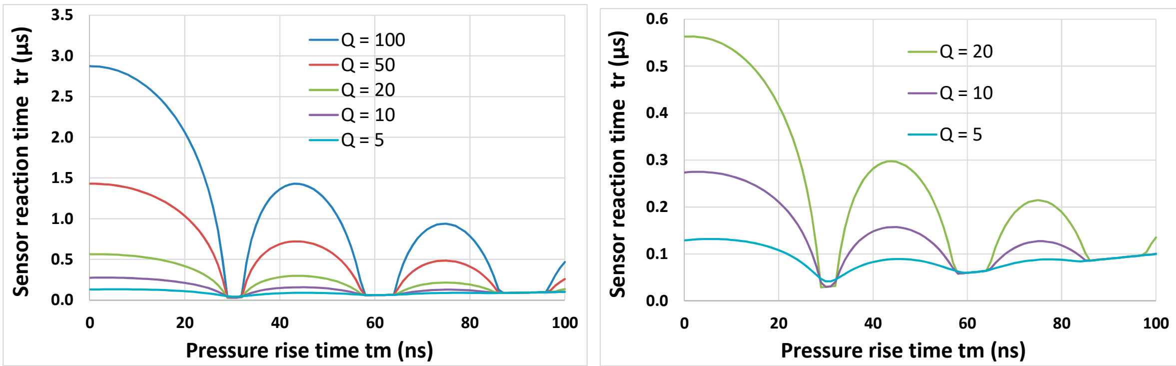

Figure 5. Sensor reaction time versus pressure rise time for different Q factor.

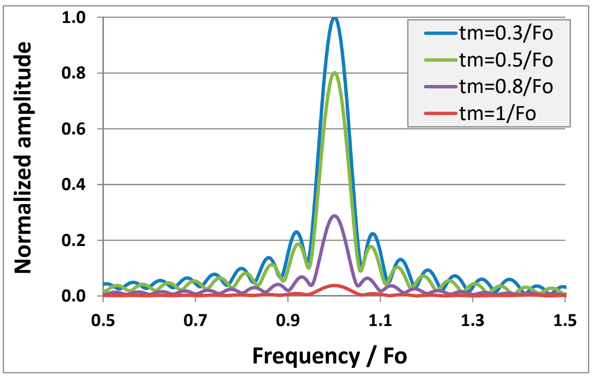

Figure 6. Amplitude of fundamental mode versus t_m (Abaqus simulations results).

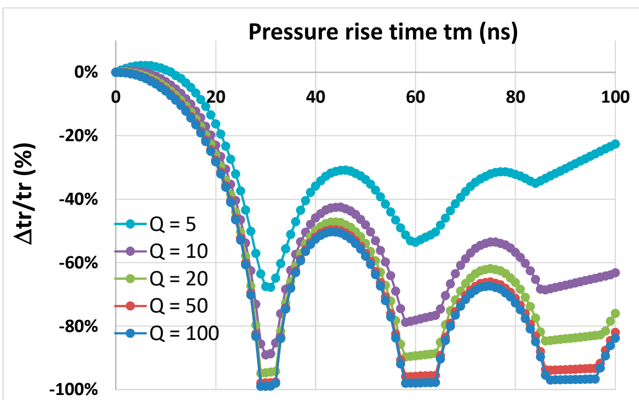

Figure 7. Relative sensor reaction time versus pressure rise time for different Q factors.

4. Conclusions

The dynamic mechanical behavior of membrane-based piezoresitive sensors was modelled by a second order transfer function with non-zero pressure rise time. For miniaturized silicon membrane (5 μm × 30 μm × 90 μm) the fundamental resonant frequency F_o is of 33 MHz. The results show that pressure rise time tm larger than $1/(3F_o)$ plays a crucial role for the accurate estimation of the sensor reaction time. Consequently, when designing ultra-fast sensors for pressure air blast monitoring, the increase of frequency F_o for a given rise time is expected to provide a significant reduction of the sensor reaction time.

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