Modelling and analysis of bandwidth on CMUTs for medical imaging

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Abstract. The bandwidths of capacitive micromachined ultrasonic transducers (CMUTs) affect the resolution of the ultrasound image. This paper analyzes the factors affecting the bandwidth, defines the form of the gain bandwidth product, and studies the maximum condition of the performance metric. Using MATLAB simulation calculation, the parameters of the CMUT bandwidth and gain bandwidth are simulated in transmit and receive modes. The influence of the product provides a theoretical basis for further design of the composite CMUT, increasing the bandwidth and thus improving the resolution of the ultrasound image.

1. Introduction

Ultrasound technology has been a hot research topic since the 20th century, and it has been widely used in medical diagnosis, non-destructive testing, medical ultrasonic therapy, ultrasonic microscopy and oceanographic profiling [1]. In medicine application, ultrasound imaging has the advantages, such as safety, portability, ease of use, and low price. Moreover, ultrasound imaging has great potential in real-time monitoring, quantitative analysis, and treatment planning. The analysis of medical images by computer can provide medical experts with more accurate diagnostic data, so that medical experts can get rid of observation and diagnosis. Therefore, the analysis of medical ultrasound image has long been concerned by researchers [1].

With the development of microelectromechanical systems (MEMS), micro-ultrasonic transducers have emerged. Compared with traditional piezoelectric ultrasonic transducers, they have the advantages of small size, low cost and a broad bandwidth. With the development of MEMS technology and technology, capacitive micro-ultrasonic transducers have gradually become a hot spot in current research. Except for easy to integrate with the circuit, reduced interference signals [2-3], CMUT also has the advantages of high sensitivity, high frequency bandwidth and high electromechanical conversion efficiency [4]. However, in recent years, the study on bandwidth and gain bandwidth is relatively few. In designing the transducers, some parameters affecting the bandwidth should be rationally designed to improve the efficiency of CMUT design and manufacturing. In order to increase the bandwidth of CMUT and improve the resolution of ultrasound image, this paper studies the relevant mechanism and applications of the bandwidth influencing factors of micro-ultrasonic transducers, and establishes a mathematical model to study the membrane radius(a), membrane thickness(tm), vacuum cavity height (tg)and electrode through simulation. The gain bandwidth product helps to promote the maturity and perfection of related technologies, further promotes the development of CMUT.
2. Working principle and model

A capacitance is formed between the upper and lower electrodes of the CMUT. When a DC voltage is applied between the upper electrode and the lower electrode, the electrostatic force pulls the upper electrode membrane toward to the silicon substrate, therefore causes the deformation of the film. If AC is applied, the deformation will be from small to large, from large to small, which causes the vibration of the membrane to generate sound wave. If the frequency range of the vibration is in the ultrasonic range, ultrasonic waves are formed; on the contrary, when the CMUT used as the receiving end, the two poles are properly biased by DC, the membrane will vibrate under the action of ultrasonic waves, and the spacing between the two electrode plates will change, so that the capacitance value formed by the two electrode plates will change with the vibration of the membrane, resulting in detectable electrical signal. Ultrasonic information is detected. A single CMUT can act as either a transmitting transducer or a receiving transducer. The membrane thickness (tm) is usually 0.5-2 μm, which the membrane radius (a) is 20-100 μm [5].

According to the vibration theory of the thin plate, the mechanical impedance of the membrane of CMUT can be derived. For the convenience, we select a circular membrane for analysis. The Young's modulus of the circular membrane material is Y₀, the membrane tension is T, the Poisson's ratio is σ, density is ρ, the membrane thickness is tm, the radius is a, and the membrane is fixed around. When a uniform pressure P is applied to the membrane, the membrane will produce a vertical displacement x(d) from the center distance d₀ under pressure, the differential equation of displacement [6][7]:

\[
\frac{(Y_0 + T)}{12 \rho (1 - \sigma^2)} t_m^2 \nabla^4 x(d_0) - \frac{T}{\rho} \nabla^2 x(d_0) - \frac{P}{\rho L} \frac{d^2 x(d_0)}{dt^2} = 0
\]

(1)

The mechanical impedance of a capacitive ultrasonic transducers membrane is defined as the ratio of the applied force on the membrane to the average speed of the membrane.

\[
Z_m = \frac{p}{\nu}
\]

(2)

Resonance frequency of membrane [8] fr is as follows,

\[
f_r \approx \frac{2 t_m}{\pi a^2} \sqrt{\frac{Y_0 + T}{1.8 \rho (1 - \sigma^2)}}
\]

(3)

3. Theoretical analysis

For the sake of convenience of research, considering the complexity of rectangular thin research, membrane, we use circular as an example to study the bandwidth. Through the study of the transducers gain equation, the relationships between membrane radius, membrane thickness, membrane height and CMUT gain are established to further study the membrane [8].

The voltage gain of transducer is: \( g_t = 20 \log_{10}|G_t| \). The bandwidth is \( BW = f_H - f_L \). \( f_H \) is the high frequency corresponding to the transducers gain falling to 3dB; \( f_L \) is the low frequency corresponding to the transducer gain falling to 3dB. The gain formula can be used to derive the transducers gain bandwidth. The value of the transducer bandwidth is the frequency range corresponding to the gain drop of 3dB [9]. If you want to find the bandwidth of the CMUT, the parameters of the membrane are required.

The relationship between resonance frequency of CMUT and gain is obtained by MATLAB simulation. The influence of membrane radius and resonance frequency on transducers gain is calculated by this model. Fig 1 shows the effect between of different structural parameters on the CMUT gain. It can be seen from the figure that the substrate thickness is 0.3 μm when the chamber
height is 0.2 μm, the acoustic impedance is 1.5*10^6 kg/m^2. As for the effect of the resonant frequency on the CMUT gain, it can be seen that the curve rises sharply first and then rises slowly and finally tends to balance. Different resonant frequencies have different effects on the gain of the transducers. As the resonant frequency increases, the gain of the transducers decreases. The membrane thickness \( t_m \) has an effect on the transducers gain. When the membrane thickness continues to increase, the effect on the transducers gain is small and the membrane radius (a) is increased. The smaller the large transducers gain, the greater the effect of membrane thickness and membrane radius on the gain when designing the CMUT.

In the emission mode of the CMUT, both the AC voltage and the DC voltage can be used to excite the CMUT. In the transmit mode, assuming that there is an excitation voltage applied between the electrodes, the electrical port at the maximum voltage can be applied to the maximum pressure in the mechanical port. Let \( p \) be the pressure in the medium, \( P=\frac{F}{S} \); \( B \) is the bandwidth corresponding to the gain drop of 3dB at the output pressure; and the quality factor is defined as the pressure bandwidth product: \( M_T=P*B \); the output sound pressure is an important performance indicator of the CMUT. The output sound pressure can be expressed as: \( P = \omega d_m Z_d \phi \), where \( \omega \) is the working angular frequency, the formula is \( \omega = \frac{2\pi f}{\pi} \); \( d_m \) is the maximum displacement when the film vibrates; and \( Z_d \) is the medium acoustic impedance; \( \phi \) is the ratio of the average displacement of the CMUT vibrating membrane to the displacement of the membrane centric point.

It can be seen from the Fig. 2 that the resonance frequency gradually increases when the membrane radius increases. The trend is to increase linearly. When the bandwidth reaches a maximum value, the bandwidth decreases slowly as the resonant frequency increases, and finally reaches a stable value. It can also be seen that the thickness of the CMUT membrane \( t_m \) affects the bandwidth of the transducers. The effect is that the CMUT bandwidth will change approximately linearly within a certain range as the membrane thickness increases. When the membrane thickness increases gradually, the bandwidth change rate will decrease. It can be seen that the thickness of the membrane in a certain range has a great influence on the bandwidth, and reaches a maximum bandwidth. The membrane thickness \( t_m \) and the membrane radius a corresponding to the maximum bandwidth are the problems that should be considered when designing the composite CMUT.

We should consider not only the membrane radius when designing the composite CMUT, but also the effect of the cavity height \( t_g \) of the CMUT on the transducers bandwidth, as shown in Fig 3. \( t_g \) is the cavity height (black is 0.2μm, blue is 0.6μm, red is 1.2μm). As the membrane radius increases, the CMUT bandwidth rises first and changes rapidly, reaching a peak bandwidth, and then the bandwidth slowly decreases. When the membrane radius a is between 0 and 12 um, the cavity height of the CMUT may have an effect on the bandwidth. The cavity height has little effect on the CMUT bandwidth. So if you want to design a large bandwidth when designing a composite CMUT, you can pass the membrane radius corresponding to the peak bandwidth. The MATLAB simulation calculation can be used to obtain the simulated values of membrane radius, bias voltage and transducers bandwidth, and pressure bandwidth product.

![Figure 1. Resonance frequency on gain](image1)

![Figure 2. Resonant frequency on bandwidth](image2)
As shown in Fig. 4, we can see that the position of the thin electrode has little effect on the bandwidth. This also shows that the bandwidth of the CMUT is determined by its structure. The capacitance of the CMUT does not affect the bandwidth. When designing the composite CMUT, the influence of the electrode position on the bandwidth is not considered. As shown in Fig. 5, the bias voltage ratio has little effect on the CMUT bandwidth at 0.3, 0.45, and 0.6 respectively.

As shown in Fig. 6, the height of the vacuum chamber is 0.2 μm, 0.6 μm, and 1.2 μm respectively. The relationship between the pressure bandwidth product and the film radius can be got from the figure. When the membrane radius is gradually increased, the $M_T$ will rise slowly. When the membrane radius is greater than 60 μm, the pressure bandwidth product tends to an equilibrium value. The membrane radius with 0–60μm will affect the pressure bandwidth product. When it is larger than 60μm, the membrane radius has little effect on the pressure bandwidth product. When the vacuum chamber height increases, the pressure bandwidth product will increase. The bandwidth product has an impact, since the vacuum chamber height will affect the pressure of the CMUT.

### 4. Conclusion

Through the above simulation analysis, it is found that the larger the membrane radius (or thicker of membrane) under the emission working conditions, the higher the pressure bandwidth product. However, the bandwidth is small, and the bandwidth is independent of the height of the vacuum chamber. When the dielectric impedance, radius and thickness of the membrane are under receiving operating conditions, the gain bandwidth product and bandwidth are affected. There is a suitable medium acoustic impedance to maximize the gain bandwidth product. The vacuum cavity height also affects the gain bandwidth product and the bandwidth of CMUT. As the membrane radius increases, the bandwidth decreases and the transducers gain increases. The inductor gets a higher gain and does not affect the bandwidth. This provides a good basis for the design of composite CMUT in the future, which is of great significance for improving the ultrasonic resolution of the transducers.
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