Highly sensitive electronic stethoscope based on non-uniform PVDF curvature structure

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Abstract: Electronic stethoscope is an instrument used for auxiliary determination of patients' physical condition by collecting and processing heart sounds and lung sounds. Since traditional electronic stethoscopes have low sensitivity and poor low-frequency response, a novel electronic stethoscope is provided in this paper using curved PVDF clamping structure with non-uniform curvature based on the structure of PVDF and silicone rubber substrate. Theoretical analysis and comparison by means of the corresponding inhomogeneous string vibration model show that sensitivity significantly increases for non-uniform curvature than the uniform one. Furthermore, a new electronic stethoscope pickup is developed based on the optimal parameters at the point of maximum sensitivity of non-uniform curvature. Experiment results show that the sensitivity of the pickup can reach 1.7 mV/Pa, which increases by 13.3% compared to the one with the structure of uniform curvature PVDF and silicone rubber substrate that has been studied in recent years. Moreover, flat frequency response characteristics can be retained within the frequency band range of 2—2 kHz, which covers the frequency response range of cardiopulmonary sound collection, thus provides a strong guarantee for complete acquisition of heart and lung sound signals.

Key words: electronic stethoscope; PVDF; non-uniform curvature

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With the development of life science and electronic technology, for complex pathology, objective diagnosis of "smarter healthcare" is more and more dependent on medical diagnostic instruments butdoctors' subjective experience. Traditional acoustic stethoscopes are typical subjective diagnostic equipment, which have shortcomings such as low pickup sensitivity and poor anti-jamming ability, and thus they are far from meeting the needs of today's rapid medical development. For electronic stethoscopes emerging in recent years, their overall structure is generally composed of three parts: pickup, signal processing and signal output[1-4]. Pickup unit is responsible for cardiopulmonary sound acquisition which influences the output quality of cardiopulmonary sounds and is ultimately related to the reliability and accuracy of electronic stethoscope output. As shown in Table 1, sensitivity, frequency response characteristics and anti-jamming ability are three major factors in performance evaluation of electronic stethoscope pickup. Although microphones have high sensitivity, their frequency response characteristics cannot meet the cardiopulmonary sound frequency response ranges of 20—600 Hz and 100—1 500 Hz; moreover, the influence of environmental noise on microphone pickup is extremely severe due to omnidirectional pickup range. Polyvinylidene fluoride (PVDF) has strong anti-jamming ability and flat frequency response char-

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acteristic of 0.001—109 Hz, which can fully meet the requirements of cardiopulmonary sound frequency collection and thus it is an excellent choice for electronic stethoscope pickup unit[5-10]. However, flattened structure-based PVDF pickups only have a sensitivity of 0.3 mV/Pa[5], which can hardly detect weak cardiopulmonary sound signals. Aiming at the shortcomings of flattened structure, Toda M curved PVDF uniformly along the molecular direction and clamped it at both ends close to the silicone rubber substrate, which makes sensitivity output increase to five times with the traditional flattened structure, namely 1.5 mV/Pa[6]. Thereby the combination structurel of uniform curvature PVDF and silicone rubber substrate in electronic stethoscope pickups is feasible[11-12].

Table 1 Classification and characteristics of common electronic stethoscope pickups

Pickup infrastructure	Sensitivity	Frequency response characteristics	Anti-jamming capability
Microphone	~2.6 mV/Pa	50—20 kHz	Omnidirectional; low resistance to environmental noise
Flattened structure-based PVDF	0.3 mV/Pa	0.001—109 Hz flat	Unidirectional; directly contacts with the skin; easily susceptible to physiological signals
Uniform curvature PVDF and silicone rubber substrate	1.5 mV/Pa	16—3 kHz flat	Unidirectional; eliminates the influence of physiological signals via silica matching layer

This paper proposes a PVDF curved clamping structure with non-uniform curvature combined with silicone rubber substrate. Modeling analysis and experimental tests show that the pickup developed herein has the following advantages:

1) Sensitivity is up to 1.7 mV/Pa, which is increased by 13.3% compared to the combination structure of uniform curvature PVDF and silicone rubber substrate studied in recent years.

2) Flat frequency response characteristics of 2—2 kHz can cover the cardiopulmonary sound frequency range.

3) Strong anti-jamming ability with unidirectional structure can eliminat the influence of physiological signals generated by direct contact with the skin via silicone rubber matching layer.

Therefore, the pickup designed herein can well acquire heart and lung sound signals, which subsequently provides reliable data reference for denoising, classification and identification of cardiopulmonary sounds, and has great significance for promoting the development of objective "intelligent medical" diagnosis in China.

1 Overall design and analysis

1.1 Design of overall pickup system

Fig. 1 shows the overall block diagram of the electronic stethoscope pickup designed in this paper.

PVDF is attached closely onto the upper surface of silicone rubber in a non-uniform curvature structure, with both ends clamped by the casing part to enhance sensitivity. Silicone rubber, as the propagation medium of cardiopulmonary sounds, not only achieves impedance matching and coupling between human muscle tissues and PVDF to reduce cardiopulmonary sound attenuation in the propagation process, but also eliminates the influence of physiological electrical signals generated by direct contact with the skin to improve the anti-jamming ability. Charge-voltage converter finally outputs the cardiopulmonary sound signals collected by PVDF in the form of voltage.

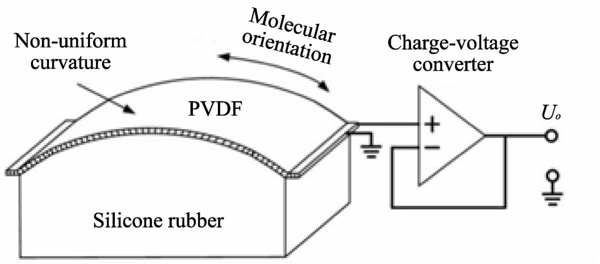

Fig. 1 Overall block diagram of pickup

1.2 Modeling analysis of non-uniform PVDF curvature structure

Two-end clamped PVDF structure is similar to inhomogeneous string vibration. According to the analyses of Refs. [6] and [12], we can know that only deformation along the curved direction of PVDF generates charges, therefore the three-dimensional wave equation can be simplified into two-dimensional wave equation.

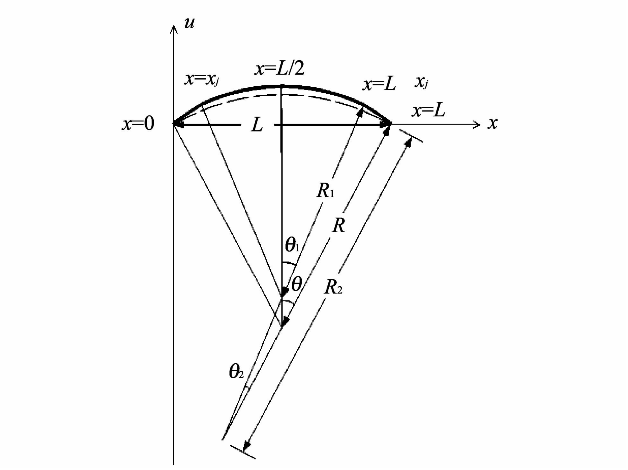

Fig. 2 Curved clamping structure and its rectangular coordinate system

As shown in Fig. 2, rectangular coordinate system is established along the PVDF molecular orientation plane. Black bold line represents the PVDF which is in a curved structure with non-uniform curvature, with both of its ends being clamped to (0,0) and (L, 0). Furthermore, the radius of curvature from x_j to $L-x_j$ (zone 1) is R_1 with opening angle is 2θ; the radii of curvature from 0 to x_j and from $L-x_j$ to L (zone 2) are R_2 with opening angles of θ_2.

Assume that PVDF forcedly vibrates by the action of upward driving force $F_{\mathrm{P}}=A\sin\omega t$ that is parallel to the u axis, where A and ω are the intensity and frequency of heart sound radiation, respectively, its wave equation can be expressed as

$$\frac{\partial^2 u}{\partial t^2}=\frac{T}{\rho_{\mathrm{P}}}\frac{\partial^2 u}{\partial t^2}+F_{\mathrm{P}}. \tag{1}$$

and the corresponding boundary conditions are

$$u(0,t)=0, \tag{1.a}$$

$$u(L,t)=0, \tag{1.b}$$

$$u(x,0)=\begin{cases}\sqrt{R_2^2-\left[x-R_2\sin\left(\frac{\theta_2}{2}+\tan^{-1}\frac{u_j}{x_j}\right)\right]^2}+R_2\cos\left(\frac{\theta_2}{2}+\tan^{-1}\frac{u_j}{x_j}\right) & 0\leqslant x<x_j,\\ \sqrt{R_1^2-\left(x-\frac{L}{2}\right)^2}-R_1\cos\theta_1+u_j & x_j\leqslant x\leqslant L-x_j,\\ \sqrt{R_2^2-\left[x-L+R_2\sin\left(\frac{\theta_2}{2}+\tan^{-1}\frac{u_j}{x_j}\right)\right]^2}+L-R_2\cos\left(\frac{\theta_2}{2}+\tan^{-1}\frac{u_j}{x_j}\right) & L-x_j<x\leqslant L,\end{cases} \tag{1.c}$$

$$\frac{\partial u(x,0)}{\partial t}=0. \tag{1.d}$$

In Eq. (1), ρ_{P} and T are the density of PVDF and tension on its each point, respectively. Since θ_2 is very small while R_2 is large, two arcs with a radius of R_2 are replaced by straight lines in Eq. (1.c) to simplify the operation. Hence Eq. (1) can be rewritten in the following form as

$$u(x,0)=\begin{cases}\sqrt{\frac{(R_2\theta_2)^2-x_j^2}{x_j}}x, & x\leqslant x<x_j,\\ \sqrt{R_1^2-\left(x-\frac{L}{2}\right)^2}-R_1\cos\theta_1+\sqrt{(R_2\theta_2)^2-x_j^2}, & x_j\leqslant x\leqslant L-x_j,\\ -\frac{\sqrt{(R_2\theta_2)^2-x_j^2}}{x_j}(x-L), & L-x_j<x\leqslant L.\end{cases} \tag{2}$$

Solving the above equation using variable separation[13], we can get

$$u(x,t)=\left\{\int_0^t\left[\frac{1}{\omega_n}AL\sin\frac{n\pi}{L}\sin\omega\tau\sin\omega_n(t-\tau)\right]\mathrm{d}\tau+\frac{2}{L}\cos\omega_n t\int_0^L u(\xi,0)\sin\frac{n\pi}{L}\xi\mathrm{d}\xi\right\}\sin\frac{n\pi}{L}x, \tag{3}$$

where $\omega_n=\frac{n\pi}{L}\sqrt{\frac{T}{\rho_{\mathrm{P}}}}$ is the resonant frequency of the PVDF structure. Eq. (3) describes the displacement of each PVDF point in the u-axis direction by the action of heart sound radiation force F_{P}, then the relative displacement of each point is

$$\Delta u(x,t)=u(x,t)-u(x,0). \tag{4}$$

Therefore, by using curve integral, final length deformation of PVDF curved clamping structure with non-uniform curvature can be obtained by

$$\Delta \mathrm{L}_{non}(\mathrm{t}) = \int \Delta \mathrm{u}(\mathrm{x},\mathrm{t}) d\mathrm{s} =$$
$$\int \left\{ \left\{ \int_0^{\mathrm{t}} \left[\frac{1}{\omega_{\mathrm{n}}} \mathrm{AL} sin\ \frac{\mathrm{n}\pi}{\mathrm{L}} sin\,\omega\tau sin\,\omega_{\mathrm{n}}(\mathrm{t}-\tau) \right] d\tau + \right.\right.$$
$$\left.\left. \frac{2}{\mathrm{L}} cos\,\omega_{\mathrm{n}} \mathrm{t} \int_0^{\mathrm{L}} \mathrm{u}(\xi,0) sin\ \frac{\mathrm{n}\pi}{\mathrm{L}} \xi d\xi \right\} sin\ \frac{\mathrm{n}\pi}{\mathrm{L}} \mathrm{x} - \mathrm{u}(\mathrm{x},0) \right\} d\mathrm{s}. \quad (5)$$

1. 3 Theoretical comparison of sensitivity between uniform and non-uniform curvature structures

Based on theoretical modeling analysis of the non-uniform curvature in the previous section, lengthwise deformation of PVDF curved clamping structure with uniform curvature can also be obtained by the same modeling approach as

$$\Delta L_{\mathrm{uni}}(t) = \int \Delta v(x,t) \mathrm{d}s =$$
$$\int \left\{ \left\{ \int_0^{t} \left[\frac{1}{\omega_n} AL \sin \frac{n\pi}{L} \sin\omega\tau \sin\omega_n (t-\tau) \right] \mathrm{d}\tau + \right.\right.$$
$$\left.\left. \frac{2}{L} \cos\omega_n t \int_0^{L} v(\xi,0) \sin \frac{n\pi}{L} \xi \mathrm{d}\xi \right\} \sin \frac{n\pi}{L} x - v(x,0) \right\} \mathrm{d}s, \quad (6)$$

where $\Delta v(x,t)$ and $v(x,t)$ are the relative displacement and absolute displacement of each PVDF point with uniform structure, respectively, and $v(x,0) = \sqrt{R^2 - \left(x - \frac{L}{2}\right)^2} - R\cos\theta$ is the initial displacement of uniform curvature structure.

As PVDF works in a stretch mode, it can be easily seen from the quantitative analysis that under the same acting force, the greater the length of tensile deformation, the larger the amount of charges generated and the higher the sensitivity[14]. Hence

$$\Delta L(t) = \Delta L_{\mathrm{non}}(t) - \Delta L_{\mathrm{uni}}(t). \quad (7)$$

Length deformation difference of the non-uniform and uniform curvature structures under the same acting force is characterized. If the difference is greater than zero, it indicates that the non-uniform structur has higher sensitivity; if the difference is less than zero, sensitivity of the non-uniform structure is lower.

Fig. 3 compares the length deformations between uniform and non-uniform curvatures uncer the same acting force F_{P} obtained by taking different non-uniform curvature locations x_j and their differences.

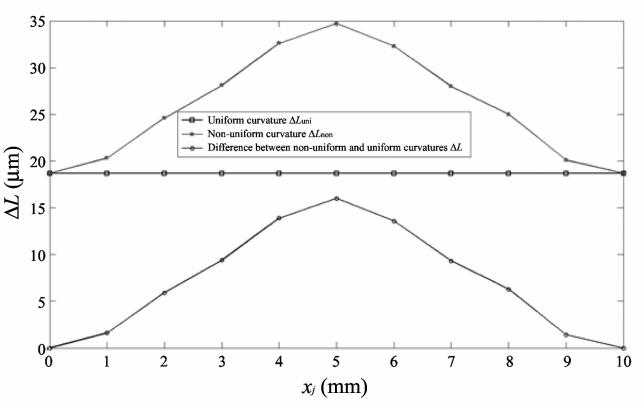

Fig. 3 Length deformations of non-uniform and uniform curvatures and their differences

ΔL represents the length deformation of uniform curvature , which is not influenced by the location x_j of non-uniform curvature and remains at 0. 018 7 mm. ΔL_{non} represents the length deformation of non-uniform curvature, which reaches the maximum (0. 034 7 mm) when the non-uniform curvature is formed at 1/4 both clamped ends of PVDF. This indicates that the length deformation difference ΔL between non-uniform and uniform curvatures reaches the maximum, which is positive as well. Therefore, when the location x_j of non-uniform structure is at 1/4 both clamped ends of PVDF, the non-uniform structure has the maximum sensitivity difference from the uniform structure.

2 Test methods and results

Based on the above analysis and comparison of sensitivity between the non-uniform and uniform structures, the electronic stethoscope pickup designed herein adopts a combination structure of non-uniform curvature PVDF and silicone rubber substrate, where the length of PVDF is 20 mm and the location x_j of non-uniform curvature is 5 mm at which the length deformation difference between the non-uniform and uniform structures is the maximum.

To accurately test the sensitivity of the pickup, an acoustic radiation model approximating human muscle structure should be designed ideally, which can generate 20 — 600 Hz and 100 — 1 500 Hz heart and lung sound radiation signals of respectively. However，such model is very difficult to be designed. Vibration exciter is an ideal vibratory signal generator，whose vibration head has acoustic radiation impedance close to that of the human muscle tissues. Thus，vibration exciter can be used to simulate the 20—600 Hz and 100—1 500 Hz human cardiopulmonary sound signals to minimize test errors.

Pickup testing protocol is designed as shown in Fig. 4.

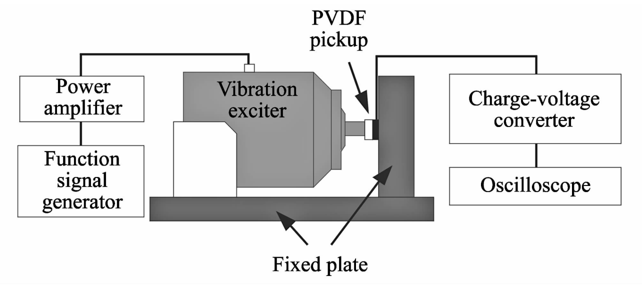

Fig. 4 Frequency response characteristics and sensitivity testing protocol of pickup

Specific frequency sinusoidal signals generated by function signal generator drive the vibration exciter to generate specific frequency，specific amplitude vibration signals via the power amplifier. Amplitude of vibration force F can be calculated from the force constant 10 N/A of vibration exciter. Contact area between vibration head and pickup is (172 × 148) mm^2，and the actual pressure acting on the pickup can be calculated by $P=F/S$.

Fig. 5 shows the sensitivity frequency response characteristic curves of electronic stethoscope pickups that are currently available in the market and have been studied in recent years.

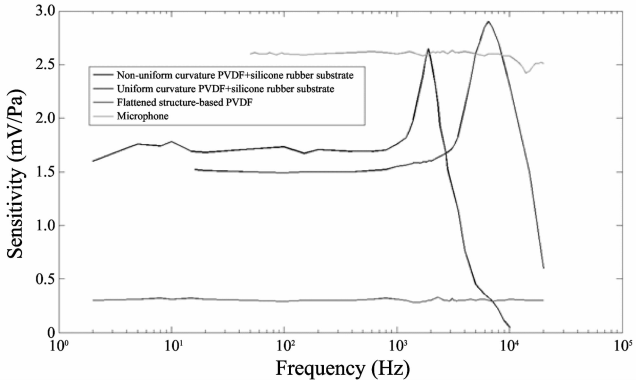

Fig. 5 Frequency response characteristics and sensitivity of pickups

Line 4 represents the sensitivity frequency response characteristic curve of the microphone，whose data are from the Panasonic WM series high-performance conference microphone available in the market. It maintains relatively flat output of 2.6 mV/Pa at a sensitivity range of 50—10 kHz，and produces valley effect at around 12 kHz. Therefore，although the microphone has high sensitivity，its low-frequency response cannot meet the frequency response range of heart sounds，which restricts its use as the heart sound pickup unit. Line 3 represents the sensitivity frequency response characteristic curve of PVDF under flattened structure. The data are from the industrially well-known 3M electronic stethoscope，which remains flat output almost throughout the entire frequency spectrum. But the output is only 0.3 mV/Pa. Line 2 represents the sensitivity frequency response characteristic curve of combination structure of uniform curvature PVDF and silicone rubber substrate studied in recent years，whose output reaches 1.5 mV/Pa at a sensitivity range of 16—3 kHz. Line 1 shows the sensitivity frequency response characteristic curve of combination structure of non-uniform curvature PVDF and silicone rubber substrate designed in this paper，whose output reaches 1.7 mV/Pa at a sensitivity range of 2—2 kHz. Its sensitivity increases by 13.3% compared to the structure of uniform curvature PVDF and silicone rubber substrate studied in recent years，which is consistent with the inference in Eq. (7) and the results of Fig. 3 in this paper. Furthermore，with frequency response characteristics fully covering the 20—600 Hz and 100—1 500 Hz cardiopulmonary sound frequency response ranges，the combination structure of non-uniform curvature PVDF and silicone rubber substrate is an excellent pickup unit for electronic stethoscopes.

Fig. 6 shows a section of normal heart sound waveforms acquired by using the pickup structure of non-uniform curvature PVDF + silicone rubber substrate designed in this paper. The waveform diagram clearly shows the locations of the first and the second heart sounds. Amplitude of the first heart sounds is markedly larger than that of the second heart sounds; besides，the locations of negative and positive amplitudes generated by systole can be seen from the first heart sounds. Therefore, the signals acquired by using this pickup well restore the heart sound waveforms, which provides strong data reference for subsequent cardiopulmonary sound denoising, classification and identification.

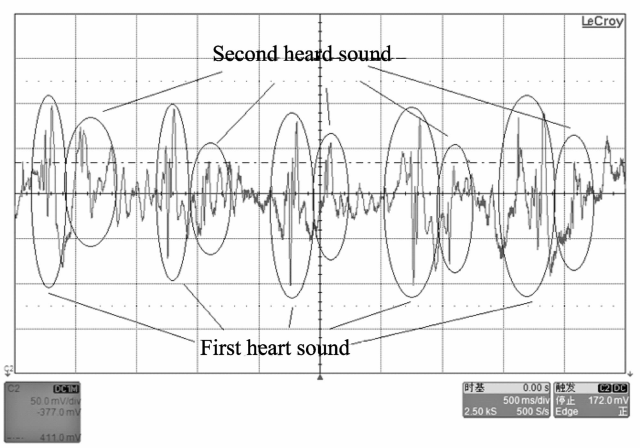

Fig. 6 Heart sound waveforms tested with the pickup

3 Conclusion

This paper presents a PVDF curved claming structure with non-uniform curvature based on the structure of PVDF and silicone rubber substrate and develops a novel high-sensitivity electronic stethoscope pickup. Theoretical analysis and comparison by creating inhomogeneous string vibration modeling prove that the non-uniform PVDF curvature has higher sensitivity than the uniform one. Experimental test shows that the sensitivity of the pickup is up to 1.7 mV/Pa, which increases by 13.3% compared to that with the structure of uniform curvature PVDF and silica substrate studied in recent years. Furthermore, test comparison with microphone, flattened structure-based PVDF and uniform curvature PVDF with silicone rubber substrate demonstrates that the pickup designed based on the combination constructure non-uniform curvature PVDF and silicone rubber substrate herein has a flat sensitivity output from 2 to 2 kHz, which covers the frequency ranges of heart and lung sounds. Compared to the microphone, flattened structure-based PVDF and uniform curvature PVDF with silicone rubber substrate of the pickup designed herein can achieve high measurement sensitivity while meeting the frequency response characteristics, which thus provides a strong guarantee for complete acquisition of heart and lung sound signals and has great significance for promoting the development of objective diagnosis of “smarter healthcare” in China.

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基于PVDF非均匀曲率半径结构的高灵敏度电子听诊器

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摘　要： 电子听诊器是利用电子技术收集处理心肺音，并依此辅助判断病人身体状况的一种仪器。针对传统电子听诊器灵敏度低、低频响应差等缺点，基于PVDF非均匀曲率半径的弯曲夹紧结构，提出了一种高灵敏度的电子听诊器设计方案。通过建立相应的非齐次弦振动模型，理论分析比较证明了非均匀曲率相比均匀曲率的灵敏度有显著提高，并优选非均匀曲率半径结构灵敏度最大的参数研制出一款新型电子听诊器拾音器。实验测试结果表明，该拾音器的灵敏度达到1.7 mV/Pa，相较近年来研究的均匀曲率半径PVDF与硅胶衬底组合结构的拾音器灵敏度提高了13.3%。该拾音器能在2—2 kHz频带范围中保持平坦的频响特性，涵盖心肺音采集的频响范围，为较完整地获取心肺音信号提供有力保障。

关键词： 电子听诊器；PVDF；非均匀曲率半径

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