PRELIMINARY INVESTIGATIONS REGARDING THE POSSIBILITY OF ACOUSTIC RESONANT APPLICATION FOR BLOOD VOLUME MEASUREMENT IN PNEUMATIC VENTRICULAR ASSIST DEVICE

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Operation monitoring and automatic control of heart supporting system require information about ventricular assist device output. One of non-invasive measurement methods is pneumatic' chamber resonant frequencies analyse. The acoustic noise brought inside pneumatic chamber is transformed by amplification or suppression of its frequency components. In consequence of this the received signal spectrum contains modified components of stimulation noise. Selected spectrum's regions parameters (like its maximal amplitude value or location along frequency axis) correlate with changes of pneumatic' chamber volume.

Keywords: heart supporting, ventricular assist device (VAD), acoustic resonant.

1. INTRODUCTION

Ventricular assist devices (VAD) are applied in case of acute circulatory system insufficiency as a bridge to heart muscle recovery or bridge to transplantation [1]. The supporting time by extracorporeal VAD's reaches from one week to a few months. Because of diversified illness reasons, personal anatomical differences, various courses of disease and treatment kinds it is necessary to adapt VAD's operation to individual requirements of patient [11]. Moreover, the supporting conditions (like arterial systemic resistance) are not stable and it can change suddenly after medicine apply or during normal, physiological cycle [2, 12]. For the sake of that the VAD's driving should ensure fast pump's operation reaction for temporary changes of patient's circulatory system state. In some cardiac assist

systems supervisory medical staff provides pump's control by its visually examination. Suitable supporting parameters (like filling/ejecting pressure, pump rate and output) are setting manually. It is allowed by extracorporeal pump's applying and possibility of membrane movement observation.

Infection risk reduction, therapy time prolongation and patient life comfort improvement require VAD implantation. Impossibility of visual device's state assessment by medical staff and supporting process controlling caused necessity of develop a suitable blood volume measurement method.

2. AIM

The following methods of blood volume measurement in extracorporeal, pneumatic VAD are known: analysis of supply air parameters (pressure and mass flow) in pneumatic chamber [3], ultrasonic blood flow measurement through the outlet cannula [4], blood's chamber electrical impedance gauging [5] and others. Disadvantages of that methods are frequently calibration necessity (because of error summation) or invasiveness (direct connection with blood indispensable to impedance measurement). Moreover, the membrane shape during pump's operation changes irregularly and unrepeatable. Because of that the theoretical considerations focused on VAD's pneumatic part analysis methods. Performed tests revealed, that specific features of acoustic waves (audible or ultrasonic) may be exploited [6, 8]. The detailed aim of studies was to test a suitability of acoustic resonant phenomenon in the audible range to estimation temporary pneumatic' chamber volume and related blood volume contained in the pump.

3. MATERIAL AND METHODS

3.1. PHENOMENON'S DESCRIPTION

The pneumatic chamber of examined ventricular assist device POLVAD (Fig. 1) consists of stiff, spherical housing and flexible membrane with separates it from blood chamber. Delivered through the connector pipe supplying air causes irregular membrane crimping and its collapsing or bulging (in diastolic and systolic operation phase, respectively). It involves significant deformation of whole pneumatic' chamber solid and its acoustic resonant properties modification. The acoustic noise brought inside this system is transformed by amplification or suppression of its frequency components. In consequence of this the received signal spectrum contains modified components of stimulation noise (Fig. 2). The variations of selected spectrum's regions parameters (like its maximal amplitude value or location along frequency axis) correlate with changes of pneumatic' chamber volume [7, 13].

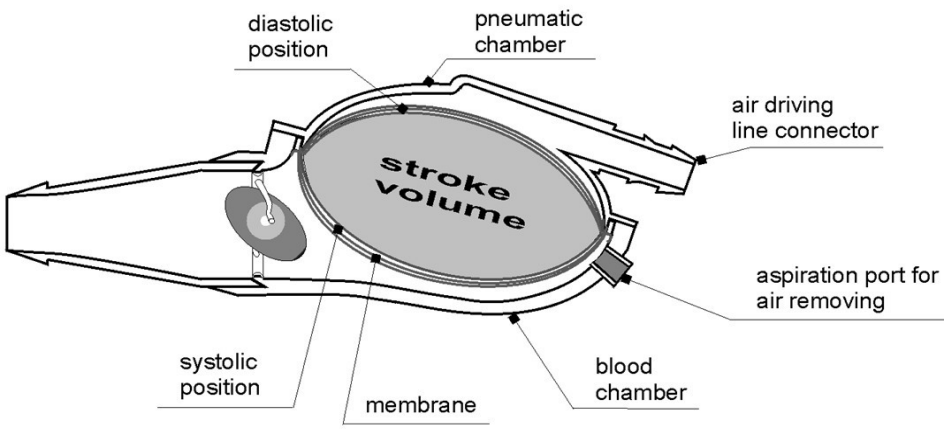


Fig. 1. Scheme of pneumatic ventricular assist device

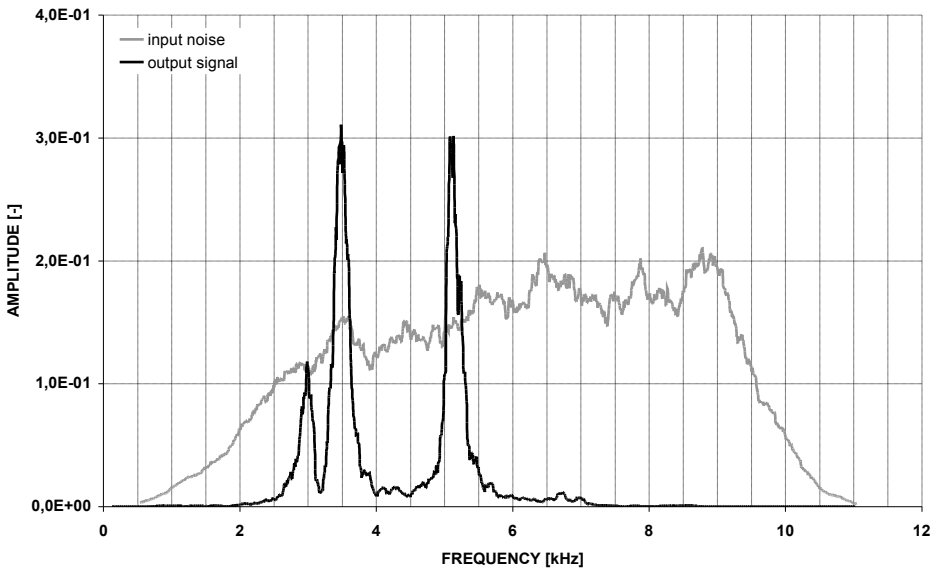


Fig. 2. Stimulation acoustic noise spectrum and its transformation by resonant properties of pneumatic chamber

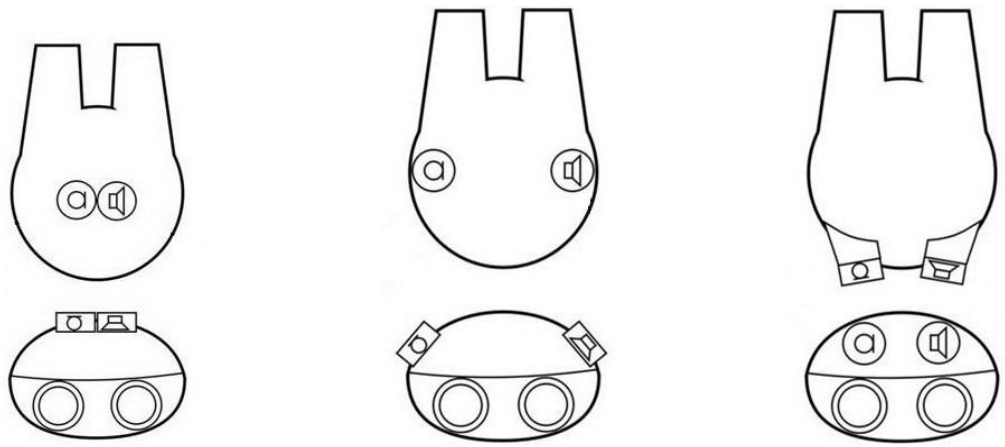
3.2. REFERENCE MEASUREMENT

Static reference method was estimation of ejected liquid height in opened to atmosphere volumetric tube by liquid hydrostatical pressure measurement. The accuracy of reference was ±1[%].

3.3. VENTRICULAR ASSIST DEVICE PREPARATION AND MEASUREMENT EQUIPMENT

Miniature acoustic emitter [9] and receiver [10] were install on pneumatic chamber of typical, clinically using blood pump POLVAD. Three different acoustic elements arrangements were tested (Fig. 3). In *first type* arrangement elements were located in the middle of pneumatic chamber by spacing adapters. In *second type* arrangement elements location was changed so as

to detector should receive acoustic waves reflected from membrane and pneumatic chamber only and could not receive emitted acoustic noise signal directly. As distinct from previous two cases where elements were mounted perpendicularly to chamber's surface, in *third type* arrangement acoustic emitter and detector were located tangentially to chamber's base at the point of membrane fixing. By this kind of arrangement the acoustic wave's path was maximized.



First type *Second type* *Third type*

Fig. 3. Various types of acoustic elements arrangement

The useful 3dB band of applied acoustic elements was 6[kHz] for emitter and 22[kHz] for receiver. It reduced a stimulation noise band. During tests the uniform spectral distributed noise was being used. The following sources of acoustic noise were tested: reverse biased P-N junction, digital white noise generator and audio white noise model.

Received acoustic signal was amplified and spectrally analysed by FFT computation. Signal acquisition was performed by NI-6259 data acquisition card on following conditions: 16[bit] resolution, sampling rate 100[kHz]. To data acquisition, processing and storing the LabVIEW experiment supporting software was used.

3.4. COURSE OF EXPERIMENT

The investigations were divided by two parts. The goal of first part was to find the most useful arrangement of acoustic elements. For that purpose the pneumatic chamber was supplied by stimulation noise and variation of received signal spectrum vs. chamber's volume were registered. In second part, for optimal acoustic elements arrangement, especially signal processing was introduced: the specific window separated from whole spectrum was approximated by polynomial and maximum of one was determined. For various load the detailed static characteristics of measurement process were determined.

4. RESULTS

The frequencies picks location evolution vs. chamber's volume were presented on cumulated charts (Fig. 4). For *first type* arrangement output spectrum (Fig. 4a) contained two groups of amplified frequencies which were moving at the opposite directions during resonant chamber's volume changes. Moreover, groups were overlapped and mixed themselves. It was not possible to find a region in whole spectrum in which picks location variations would unequivocally correlated to volume changes. For *second type* arrangement output spectrum (Fig. 4b) contained two clearly separated groups of resonant frequencies, which were moving in the direction of higher frequencies vs. blood chamber's volume increasing.

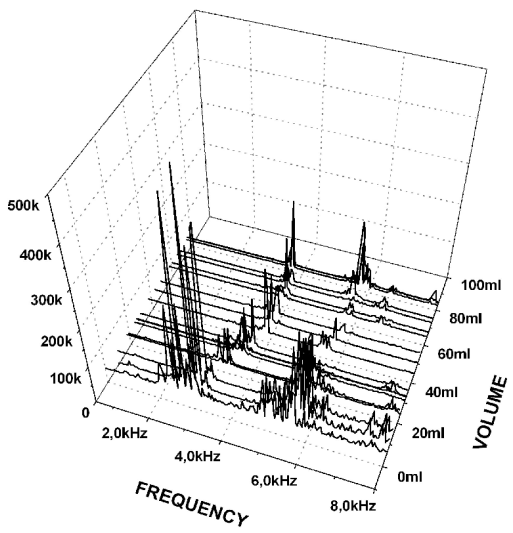


Fig. 4a

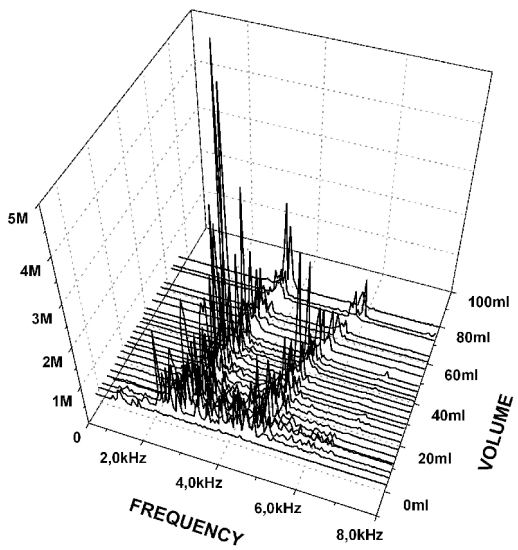


Fig. 4b

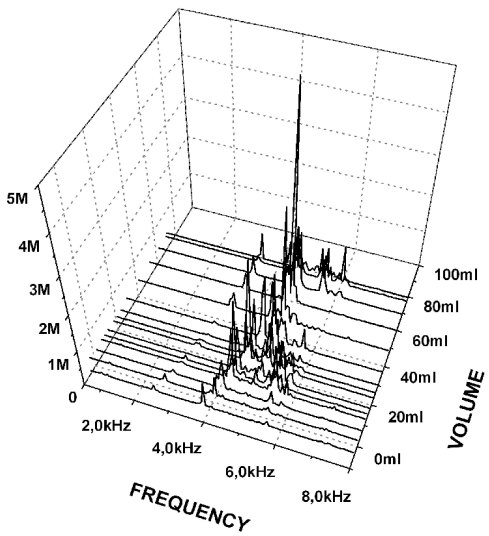


Fig. 4c

Fig. 4. Acoustic output spectrum vs. blood chamber volume

The static method's transfer function was presented on Fig. 5. Linear and 3rd order polynomial characteristic's fitting were computed. The R^2 correlation factor was 0.978 and 0.995, respectively. Output acoustic spectrum for *third type* arrangement was chaotic (Fig. 4c) and it was not possible to isolate any group of frequencies which would be suitable to further analysis.

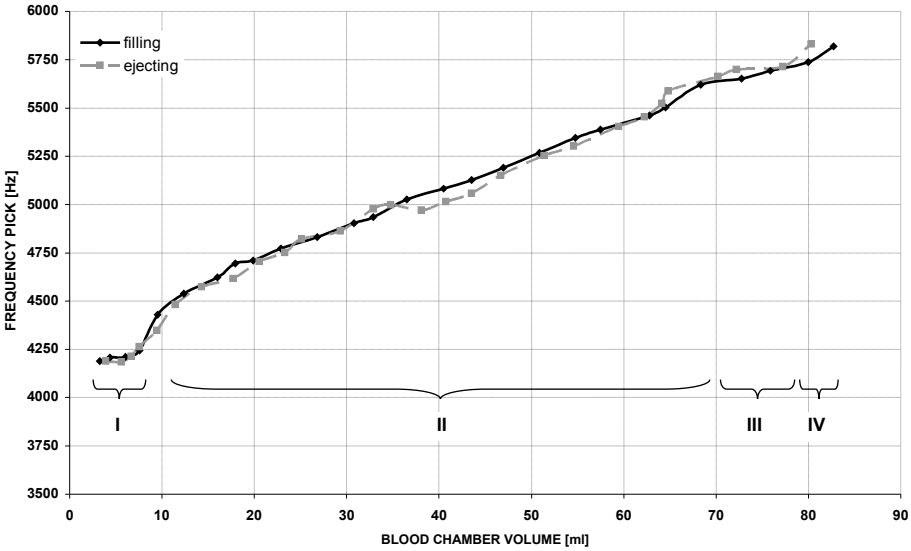


Fig. 5. Static transfer function of investigated acoustic volume measurement method

5. DISCUSSION

At the beginning of static transfer function (Fig. 5) the characteristic's nonlinearity and irregularity appeared. It is caused by specific resonant features of pneumatic chamber. This region corresponds with end of ejection phase: supply air pressure in pneumatic chamber is high (about 300[mmHg]), membrane is extremely spread and blood chamber volume equals zero. Pressure drop related to filling phase begging causes membrane releasing and low blood chamber's volume increasing, but does not cause significant pneumatic' chamber shape deformation. By that reason the resonant frequencies of pneumatic chamber are still constant (Fig. 5/I). After this phase membrane starts crimping which involves changes of pneumatic' chamber resonant properties. This fact corresponds with transfer function regularity (Fig. 5/II). At the final part of filling phase (blood chamber is full) membrane spreads again, changes of resonant chamber's shape decreasing and related part of transfer function become flat (Fig. 5/III). Because of lower supplying air pressure values (about -75[mmHg]) than in systolic phase, the transfer function irregularity is lower. At the end of measurement range (Fig. 5/IV) membrane is extremely spread close to pneumatic' chamber surface and it masks acoustic elements. Low SNR level makes impossible properly signal analysis what involves increasing

of measuring error. In the middle of volume range a differences between filling and ejecting transfer functions appeared. It corresponds with membrane moving through the midpoint of solid formed from blood and pneumatic chambers. In this point the membrane crimping is maximal but unrepeatable in following pump's operation cycles and chamber's resonant properties are not stable.

6. CONCLUSIONS

Preliminary experiments revealed that by appropriate acoustic' elements arrangement it is possible to obtain unequivocally and repeatable method's transfer function. The technical realization of investigated method does not influent on present blood chamber's construction. Moreover, it allows high insulation from blood and it is sufficient accurate (about 8[%]). By that reasons the acoustic resonant phenomenon can be applied as a blood volume measurement method in pneumatic VAD.

Long term experiments caused mechanical defect of acoustic emitter. The reason of failure were periodical supplying pressure changes and its reaction on acoustic emitter's membrane. The problem's solution is pressure equalization at the opposite sites of acoustic' elements membrane by compensation canal introducing.

Signal analysing, particularly FFT and polynomial computation, requires high processor capacity. It limited dynamic method's features to pump's speed about 60[BPM], with amounts to 6 measurements points per second. The computation efficiency improvement can be obtained by real time computer or digital signal processor applying.

ACKNOWLEDGEMENTS

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