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AN ELECTROMAGNETIC ACOUSTIC TECHNIQUE FOR NON-INVASIVE DEFECT DETECTION IN MECHANICAL PROSTHETIC HEART VALVES

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ABSTRACT

An Electromagnetic Acoustic based Technique (EMAT) has been shown to be successful in detecting strut failures in mechanical prosthetic heart valves. [1] The technique works on the basis of the differences between the acoustic resonant modes displayed by intact and fractured valve struts. The defect detection problem is complicated by the fact that the signal from the heart valve is mixed with signals from other parts of the body (e.g. heart, lungs, GI tract, noise), which have similar frequency content. In this paper, we describe the EMAT technique and a signal processing technique for the blind source identification of signals from the heart valve. Results showing the effectiveness of the method in rejecting unwanted acoustic signals are presented.

1. INTRODUCTION

Heart conditions, medically referred to as stenosis and incompetence are usually caused by the heart valve weakening and common treatment methods include replacement of the heart valve by a prosthetic substitute. This prosthetic valve is usually either mechanical or made from other biological tissue, most commonly from pigs. One kind of prosthetic mechanical heart valve that was widely implanted in patients between 1979 and 1986 was the Bjork-Shiley-Convexo-Concave prosthetic valve. This used a carbon occluder disk held in place by two metallic struts. While the outer strut is welded to the structure, the inner strut is integral to the valve suture ring. Due to the continuous loading on the outer strut, as the valve opens and closes it is noticed that the weld at one of the legs of the outlet strut occasionally fails. This as such does not cause much discomfort to the patient but further increases load on the other leg of the strut and consequent failure of the second leg would lead, nearly always to fatality. Thus there is considerable interest in detecting single leg separation in the BSCC heart valve struts.

2. ELECTROMAGNETIC ACOUSTIC TECHNIQUE

2.1 Principle

The electromagnetic acoustic technique, commonly referred to as EMAT takes advantage of the differences in the acoustic resonant frequencies of defective and intact heartvalve struts. The valve is immersed in a static magnetic field that is established using a pair of very powerful permanent magnets. An additional time varying field established using a coil excited using a tone burst is oriented in a direction that is perpendicular to the static magnetic filed and in the plane of the suture ring. This time-varying field will induce eddy currents in the suture ring. These currents, being in the presence of the static magnetic field will produce a force on the suture ring whose amplitude is proportional to the static flux density and the current induced in the strut. The direction of the force is also orthogonal to the direction of the induced current and static field. The tone frequency can be chosen to match the resonant frequencies of the intact and fractured struts and this will cause the strut to resonate, thus generating an acoustic field that can be picked up by hydrophones placed on the chest. The frequency at which the resonance occurs can be used to identify the presence or absence of a defect at the strut leg.

2.2 Modeling and Experiments

The first step in the direction of damage detection in the strut leg would be to identify the resonant frequencies of the strut in both the cases. Finite Element modeling has been performed and it has been observed that the resonant frequency for an intact outlet strut (IOS), centers around 7.5 kHz and that for a single leg separation case centers around 2.2 kHz. The Fig 1, below shows the displacement of a finite element node near the center of an intact strut, as a function of frequency. [1]

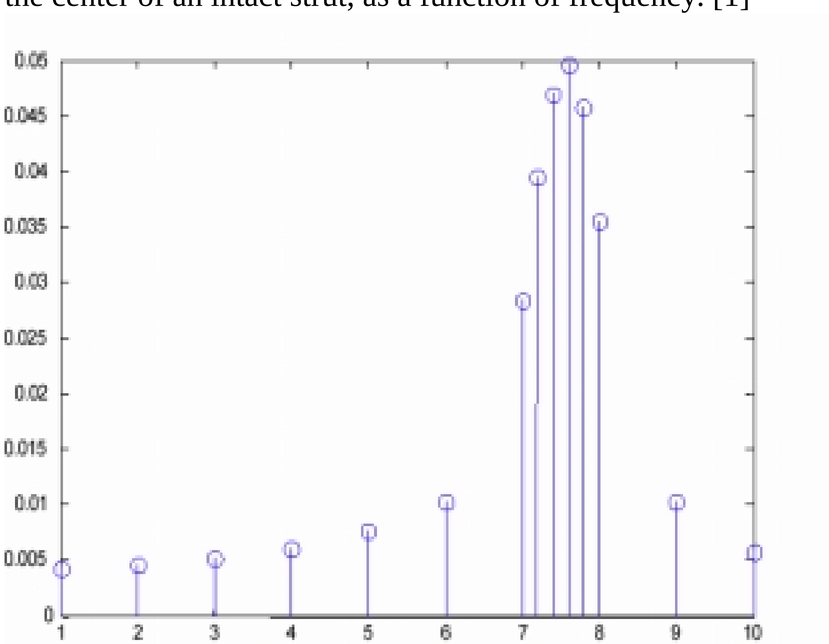

Fig. 1: Displacement vs. frequency curve for one node of a valve with IOS

Experiments have been performed to determine the resonant frequencies of the IOS and SLS situations and these also agree with the finite element model results displayed above. [2] A small prototype system, shown in Fig 2, has been developed at Michigan State University, which demonstrates the proof-of-concept. A BSCC heart valve is held in a small tank of water, which is positioned between the plates of a 3 leg magnetic circuit. The circuit is formed by 2 permanent magnets located on the opposite sides of an air gap. These magnets generate a magnetic field with a flux density of 0.9 Tesla. The time varying field is generated using two air core 175 turn coils on the opposite sides of the air gap. The field generated by the coil is approximately 87 Gauss when excited by a high current sinusoid at 7 kHz. The acoustic field is sampled by a hydrophone suspended in the tank. The frequency spectra obtained when heart valves with SLS and IOS are excited with two frequencies are shown in Fig 3 and 4. [1]

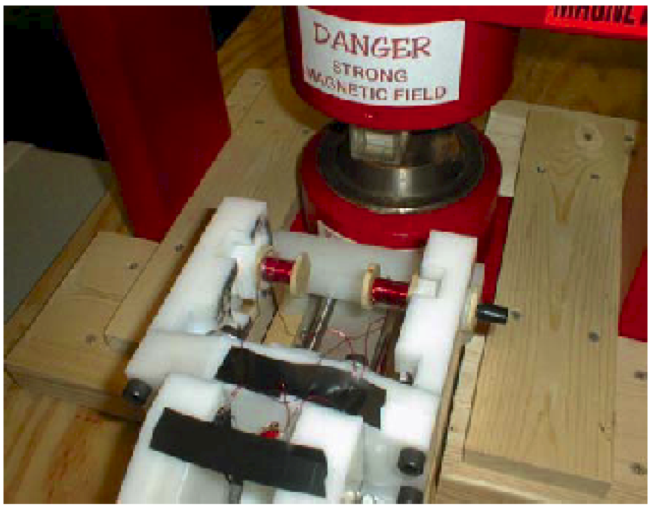

Fig. 2 : Proof-of-concept demostration unit

SLS IOS

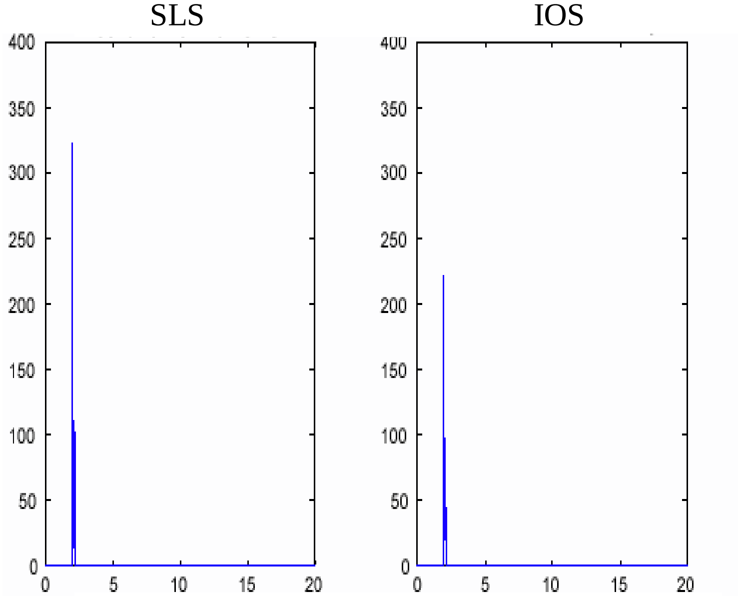

Fig 3: Frequency spectra of valves with SLS and IOS when excited at 2.075kHz

SLS IOS

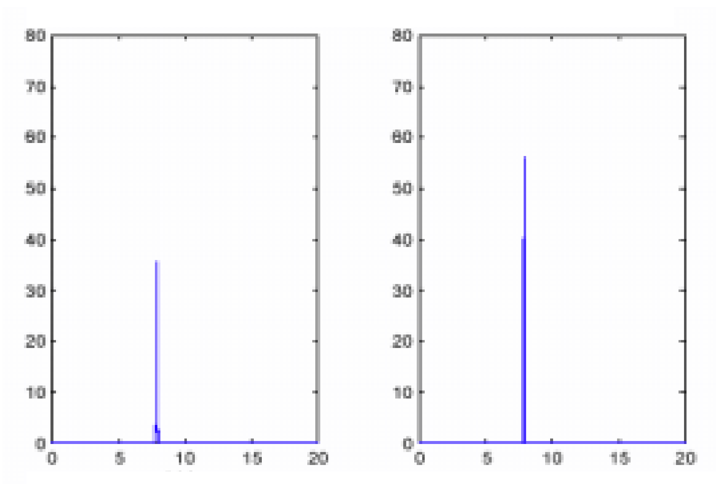

Fig. 4: Frequency spectra of valves with SLS and IOS when excited at 7.75 kHZ

2.3 Signal Processing

Thus the problem of detecting the defect in the heart-valve strut has been reduced to identifying the presence of a resonance signal from the heart valve at a particular frequency. This problem is complicated by the fact that the human body is a rich source of acoustic signals at varying frequency spectra many of which overlap with the frequency spectra of the heart valve strut (both IOS and SLS case). For instance, the sounds emanating from the respiratory tract are found to have a frequency spectrum ranging from 600 Hz to 2.5 kHz.[3] This problem limits the use of frequency domain filtering to detect the presence of the heart valve signal. Such problems, called blind source separation problems are usually solved by what are known as spatial filtering techniques. The stress in these techniques is towards detecting signals coming from a particular location in space, at a particular frequency. We, in this work, have used a combination of two existing techniques to arrive at a possible solution to the blind source separation problem. We utilize a sub-optimal algorithm based on the Maximum Likelihood principle (Wax, 1985) [4] to estimate the positions of the sources and then use another common technique, called Linearly Constrained Minimum Variance Beamforming [5] to estimate the signal.

3. SIGNAL PROCESSING FOR EMAT

3.1 Problem Statement.

We state the problem of separating the signals from the heart valve, in order to identify the resonance frequencies of the strut as follows. We assume that there are q narrow band sources, each characterized by 4 parameters. The parameters are the three coordinates of the source location and the center frequency. We also assume that p sensors receive signals from these sources. The sensor signal is given by:

$$\bar{x}(\varsigma) = \sum_{i=1}^{q} a(\bar{\phi}_i) s_i(\varsigma) + \bar{n}(\varsigma) \tag{1}$$

where

$$a(\phi) = A * e^{-jw\tau_k(\phi)} \tag{2}$$

where
s_i is the sensor signal and n is the noise vector.

Here *a* has been assumed to be a scalar function. The detection problem, now, is to identify the parameter vector ϕ, given the samples of *x*.

3.2 **Assumptions**

In solving the problem we make the following assumptions.

1. All sources are narrow band and have a unimodal spectrum.
2. All the sources can be characterized by their coordinates and their center frequencies.
3. The number of sensors is greater than the number of sources ($p \geq q$)

The approximate locations of the sources are known *a priori*.

3.3 **Solution**

The solution is carried out in two distinct stages, the first being the estimation of the locations of the various sources. This is done using the sub-optimal algorithm. The maximization of the likelihood function (*L*) is carried out using an exhaustive search. The search is conducted for the q maximums of *L*. The search is performed in the vicinity of the approximate locations. In the second step, the q corresponding values of ϕ are used to generate a suitable weight vector for the signal from the known location. The spectrum of the signal is then computed to determine if the dominant component is near either 2.2 or 7.5 KHz (SLS or IOS case respectively).

4. EXPERIMENTS

4.1 Acoustic Experiments.

As a first step, the algorithms were tested on data obtained using an acoustic experiment conducted in air with speakers and microphones. A schematic of the setup is shown in Fig 5. The three source frequencies used were 5000 Hz, 3000 Hz and 6000 Hz respectively. The final results are shown in Fig 6.

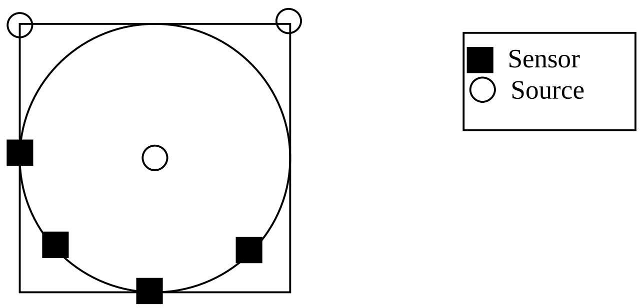

Fig 5. Set up for the acoustic experiment

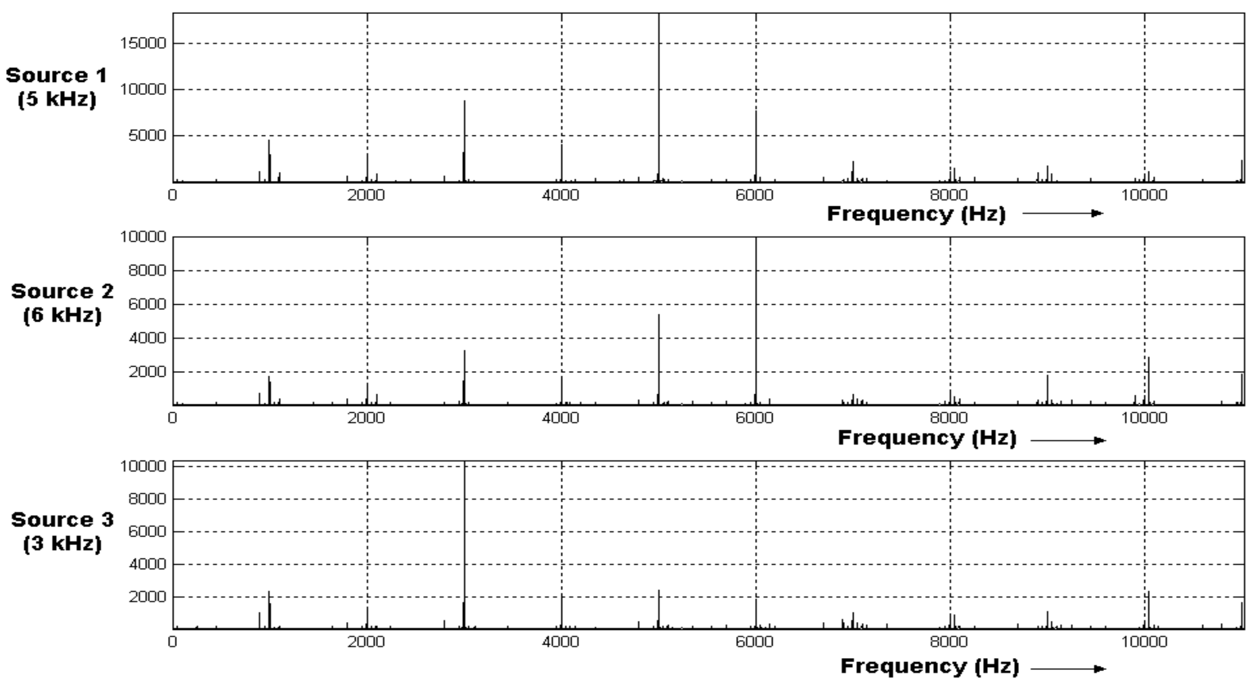

Fig 6. Spectra of estimated source signals.

4.2 Experiment on the human body

The second experiment was performed on a human body with 5 sensors placed on the chest and two interfering sources on the back. The interfering sources were generated by placing two small tweeters on the back. The source frequencies used were 500 Hz and 7500 KHz. The errors in the estimate of location in the first step are shown in Table 1 and the spectrum of the reconstructed estimate for the 7.5KHz signal is shown in fig 7.

Parameter	Source 1 (0.5 KHz)	Source 2(7.5 KHz)
Error in X (cm)	0.05	0.1
Error in Y (cm)	0.1	0.12
Error in Z (cm)	0.1	0.12

Table 1. Error in parameters. Actual reference dimension was 50 cm.

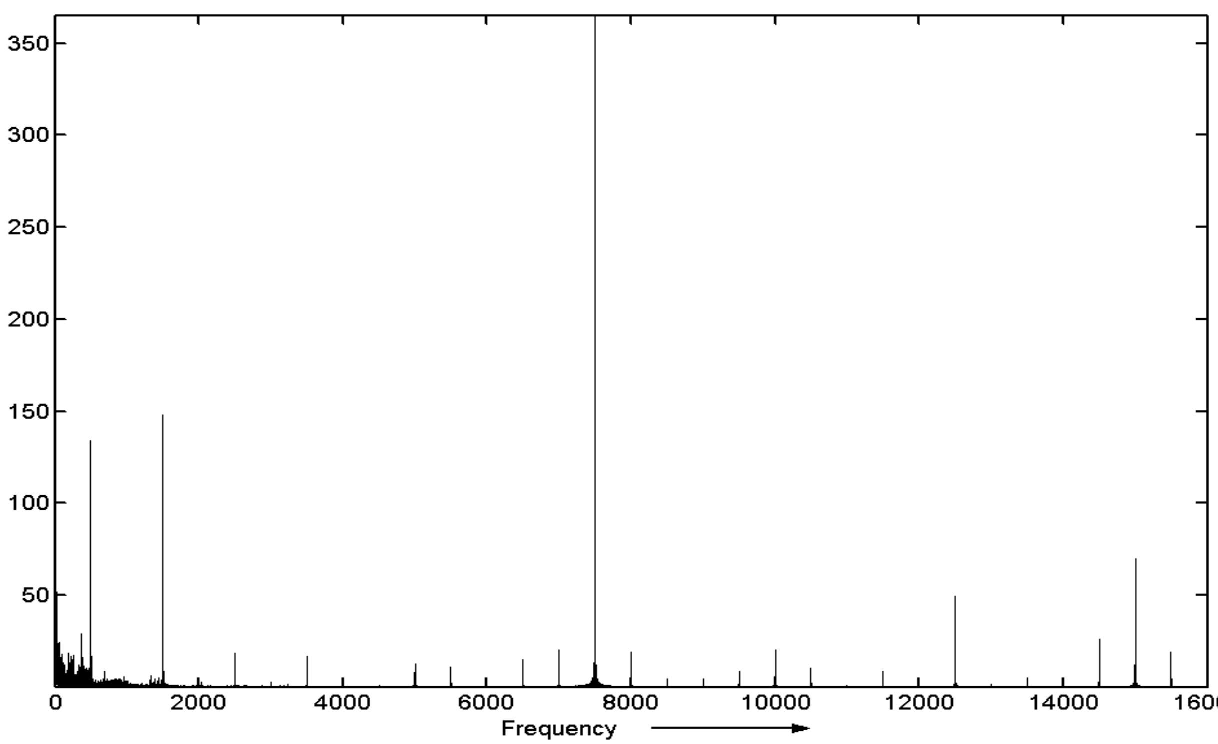

Fig. 7. Spectrum of reconstructed signal corresponding to source 2.

5. CONCLUSIONS

The initial results show considerable promise. Results show that the approach is capable of distinguishing the strut signals reasonably well and it is possible to estimate the dominant frequency. We are thus able to classify a heart valve as either having an intact or fractured strut.
Similar problems are seen to exist in the area of Acoustic Emission NDE and the signal processing techniques that are described above can be applied equally well to such scenarios as well.

6. ACKNOWLEDGEMENT

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