FREQUENCY AND TIME-FREQUENCY BASED INDICES FOR SUCTION DETECTION IN ROTARY BLOOD PUMPS

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ABSTRACT

A new suction detection system for rotary blood pumps used in Left Ventricular Assist Devices is presented. The system is based on frequency indices combined with a time-frequency extraction feature algorithm. The frequency based indices can detect the changes in the harmonic and subharmonic energy content of the pump flow signal, when a suction event is occurring. The time-frequency extraction feature algorithm can track variations in the standard deviation of the instantaneous frequency of that signal. These two pieces of information are then combined in a weighted decision system to generate a suction alarm. The proposed system has been tested in simulations, in a mock-loop system, and in-vivo tests and produced very satisfactory results.

1. INTRODUCTION

A rotary Left Ventricular Assist Devices (LVAD) is essentially a mechanical pump used in patients with congestive heart failure to assist the heart in its function, while the patient waits for heart transplantation. Unlike its pulsatile counterpart, rotary LVADs are smaller and consume less energy. The output of a rotary LVAD, however, is sensitive to afterload, i.e, to the hydraulic load they must pump against [1]. In addition, due to the fact that, at least until now, there are no reliable pressure sensors available to detect preload conditions, adaptation to venous return changes is still a missing factor in many of the control approaches reported in the literature [2, 3]. Therefore, the control problem is to adjust pump flow (PF) to accommodate physiologic demand by controlling the pump speed (PS) remains a challenge for rotary LVADs.

Two constraints should be taken into account regarding the pump speed of rotary LVADs. First, the speed can not be too low to avoid regurgitation, i.e, the return of blood from the aorta to the left ventricle through the pump (backflow). Second, the speed can not be too high to avoid suction, i.e, an event that occurs when the pump tries to draw more blood than is available and ventricular collapse may occur, which can lead to cardiac tissue damage. Suction detection, therefore, is a very important problem in the control of LVADs.

In recent years, several approaches have been used to solve the suction detection problem. These include frequency [4] and time based [5] approaches. Frequency methods are based on an empirical observation that the spectral energy content of signals, such as pump flow and pump current, changes when the patient is experiencing suction. Even though the pump is a continuous flow device, the native impaired ventricle still presents a pulsatile behavior. As a result, these signals also follow a pulsatile pattern, usually synchronized with the patient's cardiac frequency under normal operation of the LVAD, i.e, out of the range speed that could cause suction to occur. A waveform deformation index (WDI) based on power spectral density (PSD) analysis of the pump current to detect the occurrence of regurgitation and suction was proposed in [4]. The WDI is defined as the ratio of the fundamental component of the PSD to the higher PSD components. However, this ratio is not a unimodal function of pump speed (PS) and additional information is needed to decide between regurgitation and suction.

Time domain techniques are based on a beat-to-beat analysis of pump flow patterns. Usually, these patterns are compared against others in a data base with snapshots of pump flow under different conditions (normal, i.e, no suction, approaching suction, severe suction). A suction detection system based on 11 algorithms that analyze the pump flow patterns for the presence of 6 distinct suction indicators was developed in [5]. Using a window length of 5 seconds, these algorithms extract some features from the pump flow signal and compare them against snapshots of pump flow previously stored and classified in a data base by human experts.

A suction detection system that combines multiple hemodynamic indices to produce a more reliable and robust overall suction detector was investigated in [6]. Since the variability of suction patterns is high, one index may respond more effectively to a certain pattern than others. Thus, the combined response to multiple indices can identify a broad range of patterns compared with a detector based on only one index.

An approach for a suction detector in which frequency do-

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main techiques are supplemented by a time-frequency-based feature extraction algorithm of the pump flow signal has not yet been reported in the literature. In this paper, we describe such a system. The frequency domain indices SI_1 and SI_2 are related to the variation in energy of the harmonic and subharmonic bands of the pump flow signal respectively. The time-frequency feature extraction algorithm detects variations in the standard deviation of instantaneous frequency of pump flow. Figure 1 illustrates our proposed suction detection system. This paper is organized as follows: Section 2 describes the details of the frequency based indices, SI_1 and SI_2; Section 3, describes the details of the instantaneous frequency algorithm and Section 4 discusses the combination of these two sets of indices in the suction detection system. Concluding remarks are presented in Section 6.

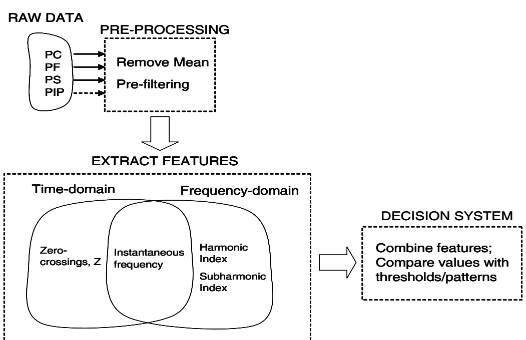

Fig. 1. Proposed Suction Detection System

2. FREQUENCY BASED SUCTION INDICES

We introduce two frequency based indices on the pump flow signal $q_P(t)$, defined as follows. The Harmonic index SI_1 is defined as the ratio of the total energy in the fundamental component frequency band to the total energy in the harmonic components frequency band i.e,

$$SI_1 = \frac{\int_{\omega_1}^{\omega_2} |Q_P(\omega)|\, d\omega}{\int_{\omega_2}^{\infty} |Q_P(\omega)|\, d\omega} \tag{1}$$

The Subharmonic index SI_2 is defined as the ratio of the signal's subharmonic energy to the fundamental energy, i.e,

$$SI_2 = \frac{\int_{0}^{\omega_1} |Q_P(\omega)|\, d\omega}{\int_{\omega_1}^{\omega_2} |Q_P(\omega)|\, d\omega} \tag{2}$$

In the above two expressions, $Q_P(\omega)$ is the Fourier transform of $q_P(t)$ and the angular frequencies ω_1 and ω_2 are defined from the signal's fundamental frequency ω_0 as $\omega_1 = \omega_0 - \omega_c$ and $\omega_2 = \omega_0 + \omega_c$, where ω_c is a threshold (in radians) which defines an interval centered at the fundamental frequency ω_0, as illustrated in Figure 2.

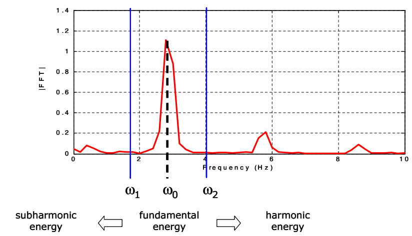

Fig. 2. Example that illustrates how ω_1 and ω_2 are derived from the pump flow spectrum

Note that our definition for SI_1 is the same as the one used in [4]. In our work, however, we estimate the fundamental frequency ω_0 from the zero-crossings rate, Z, as follows:

$$\omega_0 = \frac{\pi Z}{\Delta t} \tag{3}$$

where Δt is the window length in seconds.

In practice, before the indices are calculated, some preprocessing steps are necessary to make the signal zero mean. We first remove the mean and then low pass filter the pump flow signal $q_P(t)$ to eliminate high frequency noise. This operation also makes the signal band limited to a frequency range from 0 to 10Hz. For each time window, we then estimate the zero-crossings rate, Z, as suggested in [7], and use the result in equation 3 to calculate the fundamental frequency. These pre-processing operations are illustrated in Figure 3.

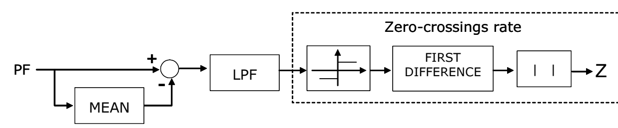

Fig. 3. Pre-processing steps and Zero-crossings calculation

Figure 4 shows an example of pump flow wave form of an in-vivo test performed in a calf at the University of Pittsburgh, with the Nimbus LVAD[1]. The data was sampled at a rate of 150Hz. Under normal conditions, i.e, out of the speed range that would cause a suction event, pump inlet pressure is positive (see Figure 4, signal at the top). In addition, pump flow resembles a sinusoid signal, i.e, $q_P(t) \approx a.\sin(\omega_0 t + \phi_0)$, as depicted in the time window A. This implies that we should expect most of the energy in the PSD of the signal to be concentrated around the fundamental frequency band, $[\omega_1, \omega_2]$. Therefore, in that scenario, we have $SI_1 > SI_2$.

As we approach a suction event (see Figure 4, time window B), the energy of the fundamental decreases and the energy of both the harmonic and subharmonic bands increases. This implies SI_1 starts to decrease and SI_2 to increase. When a suction event actually occurs, pump inlet pressure presents

[1]Nimbus Inc, Rancho Cordova, CA

negative spikes (see Figure 4, signal at the top) and the energy in the fundamental component of pump flow reaches its smallest value. Again, the energy of both the harmonic and subharmonic bands increase, but the former rises more than the later. This means that when suction is occurring, we have $SI_1 < SI_2$ (see Figure 4, time window C). In conclusion, the criteria for defining the occurrence of a suction event using both the harmonic and subharmonic indices can be summarized by the following set of If-then rules:

$$\begin{aligned} &\text{If} \quad \boldsymbol{SI}_1 > \boldsymbol{SI}_2 \quad \text{then Suction } \textbf{IS NOT} \text{ occurring;} \\ &\text{If} \quad \boldsymbol{SI}_1 \leq \boldsymbol{SI}_2 \quad \text{then Suction } \textbf{IS} \text{ occurring;} \end{aligned} \tag{4}$$

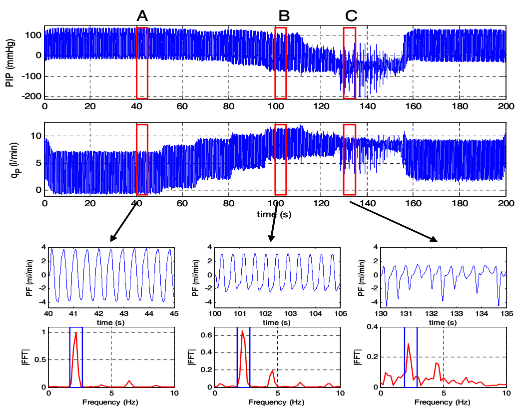

Fig. 4. Example of how PSD energy changes as suction occurs. The signals from the top are Pump Inlet Pressure (mmHg) and Pump Flow (l/min) respectively. The bottom windows are expanded segments of Pump Flow with respective spectrums.

The main advantage in defining the harmonic and subharmonic indexes as in equations (1) and (2) is that our search for a "suitable" threshold was reduced to simply measure the absolute difference between the indices. This makes the proposed suction detection system somehow adaptive, in the sense that we will not need a new threshold for a new patient or trial. Moreover, as far as we know, this is the first attempt to use the subharmonic energy content of the signal to identify suction events. Figure 5 shows simulation results of applying the harmonic and subharmonic indices to in-vivo data. Note that in this case, the indices identified correctly the occurrence of suction in PF for $130 < t < 158$. Compare this interval with the time interval for which there are negative picks in pump inlet pressure (PIP).

3. TIME-FREQUENCY BASED INDEX

The proposed time-frequency algorithm to detect suction events is based on the standard deviation of instantaneous frequency (IF) of pump flow, defined as

$$\sigma_{IF} = \sqrt{\text{var}(\langle\omega\rangle_t^{sp})} \tag{5}$$

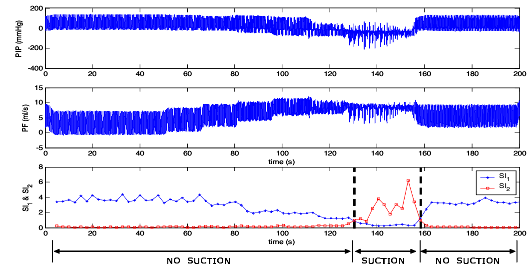

Fig. 5. Simulation result of SI_1 and SI_2 to in-vivo data. *Top*: Pump Inlet Pressure (mmHg), *Middle*: Pump Flow (l/min) and *Bottom: SI_1* and SI_2

In that formulation, the instantaneous frequency is defined as the average frequency at a given time [8], i.e,

$$\langle\omega\rangle_t^{sp} = \frac{\int \omega P_{sp}(\omega, t)\, d\omega}{\int P_{sp}(\omega, t)\, d\omega} \tag{6}$$

where $P_{sp}(\omega, t)$ is the spectrogram, the squared magnitude of the Short-time Fourier Transform (STFT) defined as

$$P_{sp}(\omega, t) = \left| \int q_P(\tau) h^*(\tau - t) e^{-j\omega\tau}\, d\tau \right|^2 \tag{7}$$

In equation (7), $h(t)$ can be interpreted as a window, which selects local sections of the signal $q_P(t)$ for Fourier analysis. In that particular application, we have chosen a kaiser window (with parameter $\beta = 5$) and time duration of 1.7 seconds. As for the previous frequency indices, we assume again that under normal circunstances $q_P(t) \approx a.\sin(\varphi(t))$, where $\varphi(t) = \omega_0 t + \phi_0$ and selecting a narrow window, it should be expected that $\langle\omega\rangle_t^{sp} \approx \varphi'(t) \Rightarrow \langle\omega\rangle_t^{sp} \approx \omega_0$.

Under that assumption, the standard deviation of instantaneous frequency should be "small" when the patient is not experiencing suction and should increase when a suction event occurs. This is acctualy the case, as shown in Figure 6.

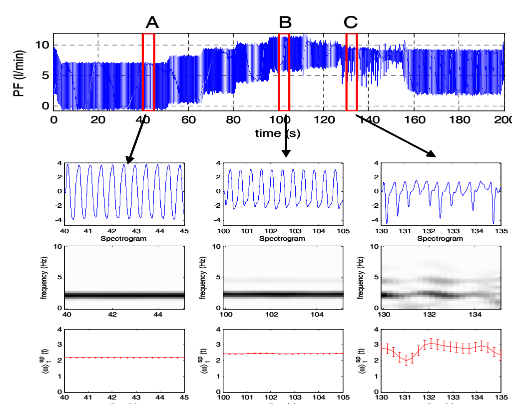

Fig. 6. Spectogram results and Instantaneous frequency of Pump Flow (l/min) for 3 time windows

4. THE DECISION SYSTEM

The main purpose of that module shown in Figure 1 is to combine the output of the frequency based indices with that from the time-frequency feature extraction algorithm. This is achieved as depicted in Figure 7. The SUCTION-ALARM is the result of a weigthed decision of the proposed indices. Note that the output due to the harmonic and subharmonic indices should be calculated first, by using the IF-THEN rules shown in equation (4).

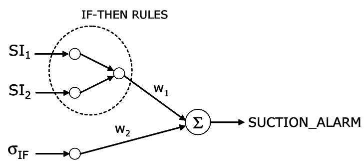

Fig. 7. Decision strategy for Suction Alarm

5. SIMULATION RESULTS

The proposed suction detection system was used to identify suction events, using in-vivo data from a calf. In that particular application, the indices were equally weighted (i.e, $w_1 = w_2$). The data were previously classified by human experts in five classes: No Suction (NS), Moderate Suction (MS), Severe Suction (SS), Not Classified/ Posterior Analysis (ND) and Not Useful (NU). This classification process has been done based on the analysis of pump flow, pump speed, left ventricular pressure and pump inlet pressure by the experts. However, only pump flow signal was used by the proposed suction detection system. Figure 8(a) shows the experts classification results. Figure 8(b) presents the specificity/sensitivity analysis of the results obtained with the proposed suction detection system (R1), compared with those presented in [5] (R2). It turns out that in the first case, i.e, specificity analysis, our results are the same as in [5] and, as for the sensitivity analysis our approach has performed slightly better than that of [5].

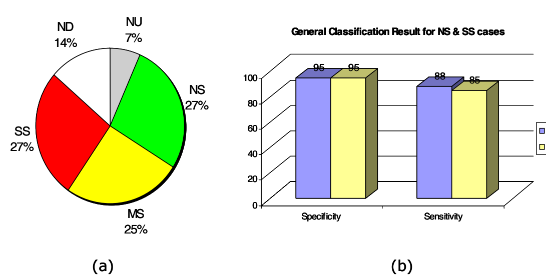

Fig. 8. (a) Expert Classification Result, and (b) Specificity/Sensitivity Analysis

6. CONCLUSION

A new suction detection system based on frequency indices combined with a time-frequency extraction feature approach was presented. The frequency based indices can detect the changes in the harmonic and subharmonic energy content of the pump flow signal, when a suction event is occurring. The time-frequency extraction feature algorithm can track variations in the standard deviation of the instantaneous frequency of that signal. Those two informations are then processed in a weighted decision system to produce a reliable suction alarm. The detection system has been extensively tested in simulations by using in-vivo data and an on-line test was recently performed in a calf, which had an implanted rotary LVAD. Preliminary analysis has shown that our proposed suction detection system was able to avoid suction in most of the cases. Ultimately, this system will be part of a feedback control strategy to automatically adjust pump speed in rotary LVADs.

7. REFERENCES

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