An Optimized Controller for Bi-level Positive Airway Pressure Ventilator*

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Abstract - This paper presents an optimized controller to achieve better synchrony in human-ventilator interactions. An experimental platform was built by using data acquisition, a set of signal collectors, and a blower wired with driver circuit. The related signals were all acquired and processed by a program written with the optimized controller in LabVIEW. Then, the comparative experiments were conducted in this paper. Specifically, in the experiments, the conventional PID controller led to the obvious pressure spike which was 2cmH_2O higher than inspiratory pressure, whereas the proposed controller can decrease the pressure quickly without the pressure spike when switching to the expiration state. Also, the Pressure-Volume Loop indicated that the area from the optimized controller was smaller than the conventional PID controller. These results showed a good performance from the proposed controller in terms of synchrony, and this optimized controller will be useful for the future ventilation.

Index Terms - PID controller, optimized controller, pressure spike.

1. Introduction

Obstructive sleep apnea syndrome (OSAS) affects 2%-4% of middle-aged adults [1], and represents the most common untreated cause of excessive daytime sleepiness. Several studies have shown that patients with OSAS have an increased accident rate in driving simulation test, and tend to have an accident rate between two and seven-times higher than patients without OSAS [2].

Clinical practices indicate that continuous positive airway pressure (CPAP) is the first line and the preferred medical therapy for OSAS patients [1], in addition, auto continuous positive airway pressure (Auto-CPAP) and bi-level positive airway pressure (BiPAP) and other noninvasive mechanical ventilator are also recommended. (1) Continuous Positive Airway Pressure (CPAP): CPAP devices delivered a positive trans-mural pressure during the throughout respiratory cycle to prevent the collapse of the upper airway [3]. (2) Auto-CPAP: it is characterized by its ability to modify the positive-pressure level by testing the changes of volume and resistance of the airway which caused by the user's apnea/low ventilation and snoring [4, 5]. (3) Bi-level Positive Airway Pressure (BiPAP): this respiratory device delivers a differentiated level of inspiratory and expiratory pressure at a preset frequency, thereby eliminating the apnoea and increasing the ventilation to avoid carbon dioxide accumulation [6, 12].

The key factor in designing ventilator devices is how to synchronize them with subject's spontaneous breathing with the improvement of compliance, that is, subject with ventilator support can breathe like the normal person do and without uncomfortable feeling, which means ideally, ventilator devices should automatically increase pressure levels at the beginning of inspiration to maintain therapeutic pressure and decrease pressure at the beginning of expiration to facilitate patient's expiration[3]. Patient-ventilator asynchrony occurs frequently in mechanically ventilated patients [7, 11], if the mechanical and natural respiratory cycles are not matched, however, the patients will be against the ventilator, causing discomfort, gas exchange deterioration and cardiovascular impairment [7, 8]. The work of breathing (WOB) is another important index to evaluate the ventilator, to better understand the scope of patient-ventilator interactions during ventilation, we recorded the WOB by both the patient and the ventilator as well. WOB is considered as the values of standard weaning criteria, and it is to indicate the work caused by patient and ventilator because of the resistance which includes the airway resistance, tissue resistance and elasticity of lung and needed overcome [9, 10].

In fact, the problem of synchronic performance between the subject and ventilator had not been totally solved yet [8, 12]. Thus, this paper aims to optimize the controller and develop a new BiPAP ventilator with better synchrony.

2. Methods

2.1 Structure of Experimental Platform

In order to simulate the respiratory system, we designed the experimental platform. Respiration of human body is based on pressure difference between atmosphere and the lung. If the pressure inside the lung is lower than the atmospheric pressure, the lung will expand and the air will be delivered, which is called inspiration; if the pressure inside the lung is higher than the atmospheric pressure, the lung will shrink and the air will be exhaled, which is called expiration. The mechanical ventilator is based on this principle and maintains the patient's lives.

The experimental platform consists of a data acquisition device(NI-6431, National Instruments, EUA), a set of signal collectors combined with pressure sensor (Freescale MPXV5004G) for pressure measurement and differential pressure transducer(163PC01D48, Honeywell, EUA) for flow

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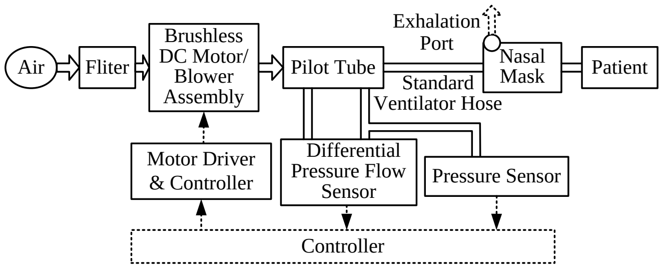
measurement, and a motor driver to control the brushless DC motor. Meanwhile, we wrote a certain program in LabVIEV to acquire and process the measurement, and generate a driving signal to regulate the rotating speed of the blower for better synchrony. The scheme of the experimental platform and the experiment conducted with a normal subject were shown as Fig.1 below:



(a)

(b)

Fig. 1 (a) the diagram of structure of the experimental platform
(b) experiment platform with a normal subject

Ambient air is drawn through the air filter by the blower and pressurized. Then, the desired pressure is delivered to the subject via the flexible tubing and a nasal mask. The pressure sensor and flow sensor will detect the varying signals and then feedback them to the controller, which in turn regulates the speed of blower by generate a control signal for the motor driver. In this paper, the ventilator with the optimized controller has two pressure levels, the inspiratory positive airway pressure (P_{IPAP}) and expiratory positive airway pressure (P_{EPAP}).

2.2 Optimized Controller

The PID controller which can realize targeted pressure by detecting flow signal is widely adopted in current ventilator. Fig.2 shows the block diagram of PID controller.

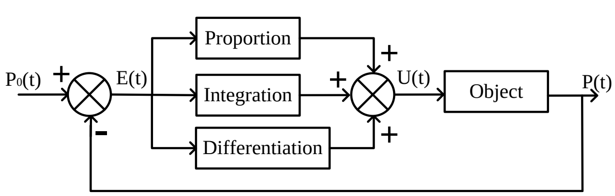


Fig. 2 The block diagram of PID controller

The E(t) and U(t) illustrated in Fig.2 can be expressed as follow:

$$E(t) = P_0(t) - P(t) \tag{1}$$

$$U(t) = K_p E(t) + K_i \int_0^t E(\tau) d\tau + K_d \frac{dE(t)}{dt} \tag{2}$$

where E(t) is the input of the PID controller, and U(t), which ultimately decides the speed of blower running, is the output of PID controller.

Note that although the PID controller can fast trigger the ventilator with desired pressure needed for subjects, however, it does not consider the respiratory cycle. Thus, we applied an optimized controller corresponded with respiratory cycle. Based on PID controller, we put forward a new model, pressure evaluate correction module (PECM), and it is shown as Fig. 3:

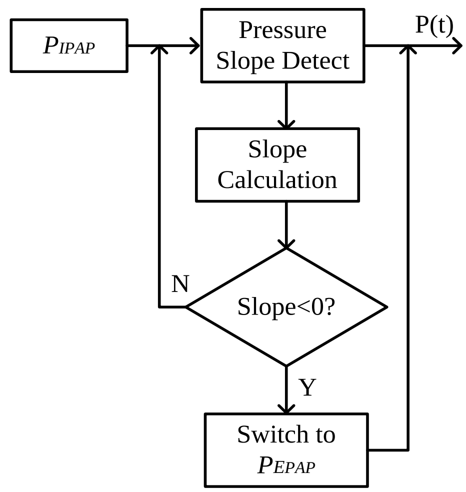


Fig. 3 The block diagram of pressure evaluate correction module

The main idea of PECM is to detect and calculate the pressure rising rate and pressure falling rate. Because when subject inhale, the flow variations will trigger the ventilator to supply the pressure correspondingly, the slope is greater than zero when it is inspiration, whereas the slope is less than zero when it is expiration. It is known that the flow threshold is a key factor to distinguish the inspiration phase and expiration phase, however, it may lead to the invalid triggering, which may indirectly increase the WOB and decrease the synchrony rate. Thus, in this paper, the optimized PECM-PID controller is shown as Fig.4:

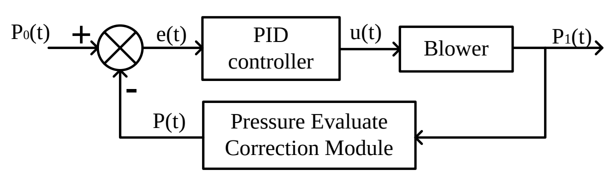


Fig. 4 The block diagram of optimized controller

For the respiratory cycle is not a constant period and the subject is a big load and disturbance for the whole respiratory system affecting the ventilator supply, in PECM-PID, the subject's respiratory period and intensity were taken as consideration, helping the slope calculation, and we set the control flag to judge the actual respiratory phases and quickly adjust the output pressure for the subject.

On the other hand, to avoid the pressure rising at the end of inspiration, the speed of motor will be slowed down in advance. Thus, the objective of optimized PECM-PID aims to ensure that the ventilator can deliver the pressure matched with the actual respiratory cycle of human body.

3. Results

To validate the efficiency of the optimized PECM-PID controller, we carried out the experiment by connecting the output port of blower to the nasal mask and applied the nasal mask to a normal subject, and we set the inspiratory positive airway pressure $P_{IPAP}=10cmH_2O$, expiratory positive airway pressure $P_{EPAP}=4cmH_2O$, and the inspiration to expiration threshold was 20 L/min. Usually, a normal breathing cycle for a subject is about three seconds to four seconds, and in this paper, the cycle was set as four seconds.

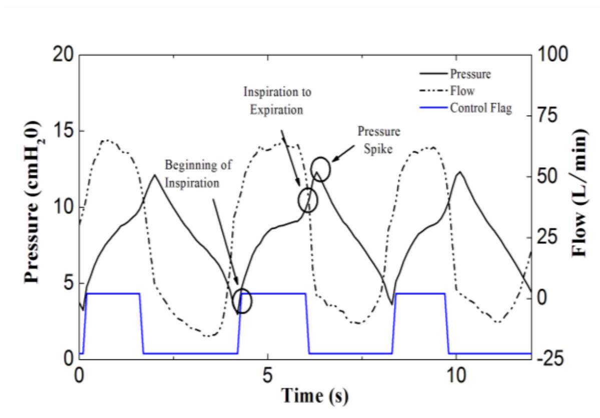


Fig. 5 The waveform of pressure and flow recorded from BiPAP ventilator with conventional PID controller

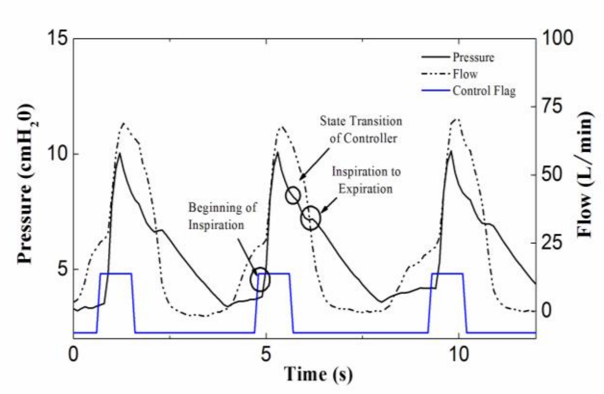


Fig. 6 The waveform of pressure and flow recorded from BiPAP ventilator with PECM-PID controller

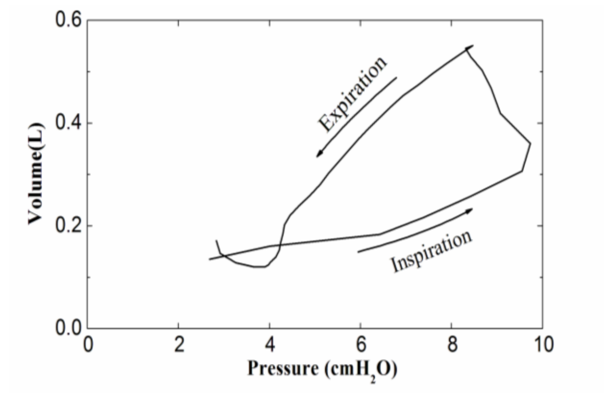


Fig. 7 The P-V loop recorded from BiPAP ventilator with conventional PID controller

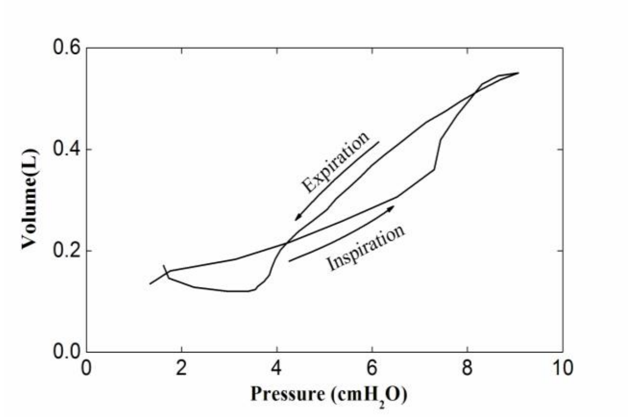


Fig. 8 The P-V loop recorded from BiPAP ventilator with PECM-PID controller

The pressure and flow waveforms during a few breathing cycles are shown in Fig. 5 and Fig. 6, which were collected by conventional PID controller and PECM-PID controller, respectively. In addition, the blue line which stands for a control flag (when inhaling, it switches to one and triggers the blower, when exhaling, it switches to zero and slows down the blower) is also depicted for indicating the inspiratory phase and the expiratory phase. Besides, we also depicted the Pressure-Volume Loop, for the entire area which the loop encompasses represents the patient's work of breathing.

By comparing Fig. 5with Fig. 6, we know that the proposed PECM-PID controller outperforms the conventional PID controller. Specifically, in Fig. 5 for the conventional PID controller, the control flag stayed at one for approximately 1.8 seconds, and the evident pressure spike with the value of $2cmH_2O$ is even higher than P_{IPAP} and appears at the initial expiration state, whereas in Fig. 6, for the PECM-PID controller, it can reach the targeted pressure ($10cmH_2O$) immediately as the control flag which stayed at one for approximately 0.8s triggered the blower when subject starts inhaling, in addition, the pressure spike disappeared ideally. Further, as to the Pressure-Volume Loop, from Fig. 7 and Fig. 8, it is clearly shown that the area from PECM-PID controller is much smaller than conventional PID controller.

4. Discussion

The purpose of this paper is to improve the human-ventilator synchronization. The whole respiratory system connected the nasal mask and the subject in this paper is approximately a closed container, even with a small exhalation port positioned near the nasal mask, most of air exhaled from the subject will inevitably come back into the hose. Meanwhile, the blower cannot stop or slow down the speed immediately even when the control flag switches to zero, which means the blower will still run for a very short time. Therefore, the pressure will rise up and it would be difficult for the subject to exhale and decrease the synchrony because of the high pressure spike. In Fig. 6, for the optimized PECM-PID controller, because the respiratory cycle is taken into account, it is clearly observed that the duration of control flag with staying at one is shorter than the conventional PID controller, which decreases the speed of blower at the end of inspiration for helping pressure falling and can effectively facilitate the subject's exhalation and improve the synchrony in human-ventilator.

5. Conclusions

The optimized PECM-PID controller introduced in this paper showed a good performance in terms of synchrony and improved the human-ventilator interaction. Comparing with the conventional PID controller, this novel controller ensures that the patient exhale easily, which can be explained by the automatic prediction of the inspiratory duration for eliminating the pressure spike. It may have a wide perspective and implementation for the ventilation. Future study may focus on how to improve the synchrony with more effectively avoiding the uncomfortable feelings of subject when using the ventilator.

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