FLOW ESTIMATION IN CPAP TREATMENT AND ASSISTED RESPIRATION

VOLUMENSTROMABSCHÄTZUNG BEI EINER BEHANDLUNG MIT KONTINUIERLICHERM POSITIVEN ATEMWEGSDRUCK UND BEI EINER ASSISTIERTEN BEATMUNG

ESTIMATION DU DEBIT DANS LE TRAITEMENT PAR VENTILATION EN PRESSION POSITIVE CONTINUE ET LA RESPIRATION ASSISTEE

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DERWENT ABSTRACT, Accession No.
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Description

Field of the Invention

[0001] This invention relates to methods and apparatus for the estimation of respiratory flow in the course of continuous positive airway pressure (CPAP) treatment or assisted respiration.

Background of the Invention

[0002] The administration of CPAP is common in the treatment of Obstructive Sleep Apnea (OSA) syndrome and Upper Airway Resistance syndrome. CPAP treatment effectively acts as a pneumatic splint of a patient's upper airway by providing air or breathable gas at a pressure elevated above atmospheric pressure to the entrance of the patient's airway. Treatment pressures in the range 4 - 20 cm H2O are commonly encountered. More sophisticated forms of CPAP include bi-level CPAP in which different treatment pressures are applied in synchronism with the inspiratory and expiratory phases of respiration, and autosetting (controlled variable treatment pressure) CPAP, as described in U.S. Patent No. 5,245,995. In all forms of CPAP treatment it is desired to maintain the treatment pressure, usually clinically determined by a physician, to be as constant as possible to maintain treatment efficacy without causing the patient undue discomfort by having to work against an unnecessarily high positive airway pressure.

[0003] Common to all forms of CPAP apparatus is a mask worn by a patient having connection via a flexible air delivery tube to a flow generator. The flow generator has a turbine driven by an electric motor that is under the control of a microprocessor-based controller.

[0004] In this specification a reference to a "mask" is to be understood as including a nose mask, a mouth mask, a nose and mouth mask in combination or a full face mask.

[0005] Simple CPAP machines estimate the mask pressure from the motor speed and operate under speed regulation. More sophisticated machines incorporate a pneumatic pressure transducer that provides a feedback signal representative of pressure at either the mask or a point within the flow generator itself. If the pressure feedback signal is from the mask, additional tubing or wires must extend between the mask and the flow generator which can give rise to sterilisation and/or safety problems. If pressure feedback is from a point within the flow generator, or at some other point removed from the mask, the impedance of the air delivery tube can result in flow-induced pressure swings at the mask. The pressure swings can be up to ±5% of treatment pressure, and since it is desired to provide the patient with the minimum treatment pressure to provide treatment efficacy and yet avoid the patient doing unnecessary work during exhalation, these pressure swings are undesirable and should be eliminated as far as possible.

[0006] It is also desirable to be able to accurately determine dynamic air flow in the delivery tube and mask. The disclosure of flow estimation based on detecting flow generator current, deriving filtered voltage and comparing the results with predetermined flow generator characteristics in CPAP treatment is disclosed in the specification of EP-A-0656216. In contrast, preferred embodiments of the present application disclose flow estimation based on detecting motor speed, current, and/or armature voltage and based on directly measured delivery tube pressure. "Flow" is to be understood as including both ventilation volume and a volumetric flow rate. The flow will have a component due to the flow generator that is modulated by patient respiration. The measurement of air flow in the air delivery tube can beneficially be used to measure the average volume breathed by the patient and to determine whether the patient is inhaling (inspiring) or exhaling (expiring), the latter of which is crucial in the implementation of bi-level CPAP. Currently this is done using an in-line sensor to directly measure flow, or by measuring the pressure drop across a restriction in the air delivery tube (or alternatively, the pressure drop along with air delivery tube). These methods require the use of additional transducers, and in some cases additional wiring or tubing to connect the transducer to an appropriate point in the control circuitry of the CPAP apparatus.

[0007] It thus also is desirable to accurately measure or estimate air flow from the stand-point of enabling advanced control over the administration of CPAP treatment and ensuring efficacy of treatment and patient compliance without reducing patient comfort.

[0008] The present invention is directed to overcoming or at least ameliorating one or more of the foregoing problems.

Summary of the Invention

[0009] According to the invention there is provided a method and apparatus as set out in the accompanying claims.

Brief Description of the Drawings

[0010] Fig. 1 is a schematic block diagram of CPAP treatment apparatus;

Fig. 2 is a cross-sectional view of the air delivery tube at the point where pressure is sensed;

Fig. 3 is a block flow diagram describing the estimation of flow;

Fig. 4 is a schematic block diagram relating to Fig. 3; and

Fig. 5 is a schematic block diagram relating to the compensation of flow-induced pressure swings; and
Fig. 6 is a chart of pressure swing versus set-point
(treatment) pressure.

(Fig. 5 and 6 do not illustrate the invention claimed)

Detailed Description of Preferred Embodiments and
Best Mode

[0011] The embodiments described relate to CPAP

treatment apparatus, however it is to be understood that

the invention equally has application in apparatus for the

 provision of assisted respiration or ventilation.

Flow Estimation

[0012] As shown in Fig. 1, the CPAP flow generator

10 is coupled to an air (or breathable gas) delivery tube

12, in turn coupled with a nose mask 14 being worn by

a patient 16. The flow generator 10 comprises a micro-

processor-based motor controller 20 that in one pre-

ferred form can include a 8-bit micro-controller such as

the Motorola ™ MC68HC805B6. The motor controller

20 is connected with an electric motor power supply 24

by a control line 22. The power supply 24 provides a

supply of electrical energy, in the preferred form being

DC, to the electrical motor 28 by a supply line 26. The

motor 28 is connected with a turbine 32 by a mechanical

coupling 30. The electric motor 28 also is connected to

the motor controller 20 by a signal line 34.

[0013] The turbine 32 provides breathable gas (in-

cluding air) to the delivery tube 12 at a pressure elevated

above atmospheric, and at a flow rate to satisfy a pa-

tient's treatment and respiration needs. This is achieved

by speed control of the electric motor 28 and depended

upon the pneumatic capacity of the turbine 32. The elec-

cric motor 28 preferably is a brushless DC type, such as

the PAPST™ ECA 27-11. This motor has integral Hall-

effect sensors that provide an electrical signal represen-

tative of motor speed provided to the motor controller

20 on the signal line 34. The electric motor 28 can alterna-

tively have connected to it an optical or mechanical

tachometer or any other convenient rotational speed-sensing
device. The speed of a DC motor is di-

rectly proportional to the armature voltage as provided by

the motor power supply 24. There is a relationship be-

tween motor speed, turbine delivery pressure and

flow that can be determined by experimentation.

[0014] In the bi-level form of CPAP, the separate in-

spiratory and expiratory treatment pressures are achieved by rapid turbine speed control, although the

use of solenoid-operated spill valves also is known in the art.

[0015] A pressure sensing tube 40 is connected with

the air delivery tube 12 at a point proximate the exit of

the turbine 32 within the casing of the flow generator 10.

The sensing tube 40 is connected with a pressure trans-
ducer 42 resulting in an electrical signal indicative of tur-

tine delivery pressure being passed to the motor con-
troller 20 on a signal line 44.

[0016] The flow generator 10, including the pressure

sensing tube 40 and pressure transducer 42, is com-

mercially available as the present applicant's Sullivan

™ III CPAP machine.

[0017] The pressure sensing tube 40 can alternatively

be ported into the delivery tube 12 at any point along the

length of that tube, or be ported into the mask 14 itself.

It further is possible for the pressure transducer 42 to

be proximate the delivery tube 12 so that there is only

a small length of tubing from a port into the delivery tube

12 to the transducer 42, with the signal line 44 thus ex-
tending out of the casing of the flow generator 10.

[0018] Fig. 2 shows, in cross-section, detail of the re-
gion of the delivery tube 12 to which the pressure sens-
ing tube 40 connects. The pressure sensing tube 40 at-

taches a pressure sensing port 50 located downstream

of an orifice plate 52. The orifice plate represents an im-

pedance that introduces a local pressure disturbance
resulting in an air recirculation region 54 and a laminar

flow region 56 extending downstream from the orifice

plate 52. The pressure sensing port 50 is located in the

recirculation region 54. Such a pneumatic recirculation

also can be achieved by a localised reduction in the di-
ameter of the air delivery tube 12.

[0019] A method of flow estimation now will be de-
scribed with reference to Figs. 3 and 4. As would be ap-
parent to one skilled in the art, the processing to be de-
scribed can readily be implemented by way of a com-

puter program. In the first step 60, the motor speed is

measured by means of the motor's Hall-effect sensors

80. From this rotational speed value, the equivalent

pressure, $p_{est}$, that would be developed by the turbine

32 for that measured speed if the flow were zero is es-
timated in step 62 by means of the pressure estimator

82, using a predetermined mathematical function.

[0020] One method of estimating the equivalent pres-

sure, $p_{est}$, is to apply the motor speed as the input to a

quadratic function, having the form:

$$p_{est} = c_1 \omega^2 + c_2 \omega + c_3$$

(1)

where $c_1$, $c_2$ and $c_3$ are constants, which may take any

value including zero, derived from previously deter-

mined pressure/speed characteristics of the turbine 32,

and $\omega$ is the motor speed. On the basis of the applicant's

Sullivan ™ III machine as described, representative co-
efficient values are $c_1 = 118$, $c_2 = 0$ and $c_3 = 0$. The

coefficients were calculated using a linear regression tech-

nique on the pressure/speed data for zero flow of the

Sullivan ™ III apparatus. The impedance of any inlet

baffle and the pneumatic circuit of the turbine affect the

coefficients.

[0021] In an alternative implementation, a higher or-
der polynomial may be used to estimate the equivalent

pressure, for zero flow, from motor speed, motor current
and/or armature voltage.

[0022] In another alternative implementation, a lookup table may be used to estimate the equivalent pressure for zero flow from motor speed, motor current and/or armature voltage based on an empirical set of measurements.

[0023] Coincidentally the speed measurement and pressure estimation with pressure steps 60.62, the delivery tube pressure, p_{est} is measured in step 64 by means of the pressure transducer 42, and p_a and p_b are passed to a differential summation device 84 whereby, in step 66, the difference between the two pressures is calculated. The output from the summation device 84 represents an estimation of flow, f_{est}.

[0024] A conventional orifice plate meter consists of a thin plate which is inserted into the air-delivery tube. The plate has a central orifice that is smaller than the diameter of the tube and ports either side of the plate for measuring pressure. The obstruction results in a constriction of the flow and a local pressure disturbance which can be measured. The flow q is determined by measuring the pressure at the sensing ports and is given by

\[ q = c \sqrt{p_1 - p_2} \]  

where c is a constant for a given configuration, p_1 is the pressure at the sensing port preceding the orifice plate and p_2 is the pressure at the sensing port following the orifice plate.

[0025] As previously noted, measurement of both pressure and flow in a CPAP machine usually requires at least two transducers. A pressure transducer is required for pressure regulation and a second transducer is required for flow measurement. The second transducer may be either a pressure transducer or a flow transducer. In the first case flow is given by equation (2), in the later case flow is measured directly.

[0026] For non-zero flow, it is seen from equation (2) that the pressure p_1 is greater than p_2. For zero flow, the pressures p_1 and p_2 are equal and can be estimated from a quadratic function of the motor speed having the form of equation (1).

[0027] For non-zero flow, p_1 is increased, to meet the increased flow, by increasing the motor speed. Therefore, the pressure estimate derived from the motor speed also increases. The change in motor speed is approximately proportional to the change in flow, then the change in p_{est} is proportional to the change in p_1. The flow f_{est} can be estimated, therefore, from the difference between the pressure estimate p_{est} and the measured pressure p_2, i.e.

\[ f_{est} = c \sqrt{p_{est} - p_2} \]

[0028] The orifice plate 52 has a 'square law' impedance, in which case the output of the summation device 84 represents "FLOW SQUARED". In such a case, the "FLOW SQUARED" value can be linearised in step 68 by the square root device 86, and then filtered in step 70 by the combination of low pass and high pass filters 90.92 to derive a "FILTERED FLOW ESTIMATE" value, that has the non-respiratory components removed. The low pass filter preferably will have an upper frequency limit of 20Hz to remove noise, while the high pass filter preferably will have a lower frequency limit of 0.1Hz to remove non-respiratory components.

**Flow Compensation (being not covered by the invention claimed)**

[0030] The performance of flow compensation, which enables flow induced pressure swings at the mask to be minimised, will now be described with reference to Fig. 5. The method of flow compensation can be utilised using the flow estimation value calculated in accordance with the method described above, or on the basis of a flow measurement made by a flow transducer.

[0031] In a preferred embodiment, the flow-generator incorporates a pressure transducer used for pressure regulation such as shown in Fig. 1. The transducer 42 measures pressure in the gas delivery circuit at a point removed from the mask. The flow induced pressure perturbations at the mask are therefore larger than that at the controlled point. The compensation of flow-induced pressure perturbations at the mask is by way of compensating control over the mask pressure, while still retaining adequate flow for respiration purposes.

[0032] Fig. 5 shows the processing performed by the motor controller 20 in performance of the flow compensation. As would be apparent to one skilled in the art, the function of the logical blocks can be implemented by way of a computer program. Both the electric motor speed and the actual measured delivery pressure are provided to a computational element 100 respectively by the signal lines 34 and 44. The computational element 100 estimates the flow in accordance with the technique described in conjunction with Figs. 3 and 4, thus the output of the computational element is the "FILTERED FLOW ESTIMATE". That signal is passed to a squarer element 102 to derive a signal representing "FLOW^2". In the alternative, where the orifice plate used to derive delivery pressure is a square-law type, then, as previously described, an estimate of "FLOW^2" is obtained directly in the flow estimation method, hence the squaring function of the squarer element 102 need not be performed. The estimated "FLOW^2" value is passed to a gain element 104 that scales the signal. The scale factor may take on any value, including one and zero, may have a positive or negative sign and may take on different values at different times. In a typical implementation, that incorporates an obstruction of the air-delivery circuit, the scale factor is zero for negative flow, i.e. when the mask pressure is less than the pressure at the
turbine, and a small positive constant, less than one, when the flow is positive.

[0033] The scaled flow signal passes by a limiter element 106, the function of which is to limit the magnitude of the "FLOW COMPENSATION VALUE" to a predetermined value to ensure stability.

[0034] By way of further explanation, when pressure is measured from within the recirculation region 54, and is the controlled variable, the mask pressure initially increases with increasing flow and then falls. The deviation from the pressure set point can be reduced, therefore, by subtracting the scaled flow estimate from the pressure set point. However, if the estimated flow is negative (i.e. the measured pressure is greater than the estimate pressure), no compensation is implemented to avoid instability due to positive feedback.

[0035] As the mask pressure varies as the square of flow, the flow compensation technique can be refined by making the compensation value proportional to the square of flow. Beyond a certain flow value, the mask pressure will begin to fall with increasing flow. It may be desired, therefore, to limit the magnitude of the compensation value. The most preferable limit would be at the turning point of the pressure/flow curve. The turning point is variable and is a function of motor speed. Alternatively, and more simply, a fixed limit could be used.

[0036] The constants in equation (1) can be calculated from recorded pressure/speed data at zero flow. For the purposes of flow compensation, the value of the constant in equation (3) may be unimportant (as it is replaced by a scaling factor), however, if required, it may be derived by fitting equation (3) to measured flow data. The complete flow compensation procedure is as follows:

1. calculate \( p_{est} \) from equation (1),
2. measure the pressure \( p_2 \),
3. calculate the compensation value \( (p_{est} - p_2) \), which is proportional to flow squared,
4. if the compensation value is negative set the compensation to zero,
5. multiply the compensation value by the scale factor,
6. limit the magnitude of the compensation value, and
7. subtract the flow compensation from the pressure error.

[0037] The control loop minimises the difference between the set pressure and the measured pressure, and at the same time minimises the difference between the pressure that should be generated for the measured motor speed and the measured pressure.

[0038] The outputs from the limiter element 106 represent the "FLOW COMPENSATION VALUE" scaled in accordance with the pressure-controlling signals. The "PRESSURE SET POINT" is compared with the measured pressure at the differential summation element 108, generating a "PRESSURE ERROR" signal. The "PRESSURE ERROR" signal and the "FLOW COMPENSATION VALUE" form the inputs to a further differential summation element 110, and in this way the control variable of "TREATMENT PRESSURE ERROR" is compensated in accordance with flow, the output from the summation element 110 passing to a controller unit 112 that provides the controlling signal to the motor power supply 24 on the control line 22.

[0039] The set point pressure may not be the mask pressure, as is the case for the arrangement shown in Fig. 1, where it is the turbine output pressure that is measured. In that case, the pressure set point has been pre-compensated by the controller unit 112 to be in relation to the point where pressure actually is measured relative to the desired mask CPAP treatment pressure.

[0040] In tests of the flow compensation methodology described utilising the CPAP apparatus described above, for a set mask treatment pressure of 10 cm H\(_2\)O, the magnitude of the pressure swings without compensation was 1.8 cm H\(_2\)O. With flow compensation in place, the swings are reduced to 0.7 cm H\(_2\)O. Over the range of 4 - 18 cm H\(_2\)O, the average reduction in the magnitude of the pressure swing at the mask reduced by respiratory flow was 64%. The data is shown in Fig. 6.

Claims

1. A method to estimate the flow of breathable gas to a patient (16) from a flow generator (10) having a turbine (32) in the administration of continuous positive airway pressure treatment or assisted respiration, including measuring the pressure of gas \( (p_{est}) \) delivered by the flow generator (10) and measuring the rotational speed \( (\omega) \) of the turbine (32), the method characterized by:

   estimating the equivalent pressure of gas \( (p_{est}) \) that would be delivered by the flow generator (10) at the measured rotational speed if there were no flow to the patient (16); and

   calculating the difference between \( p_{est} \) and \( p_{act} \) to give an estimate of the flow to the patient \( (I_{est}) \).

2. A method as claimed in claim 1, characterized by the further step of taking the square root of the flow estimate to give a linearised flow estimate.

3. A method as claimed in claim 2, characterized by the further step of filtering said linearised flow estimate to remove non-respiratory components.

4. A method as claimed in any one of claims 1, 2 or 3, whereby said step of estimating is characterized by the step of performing the calculation:
\[ p_{est} = c_1 \omega^2 + c_2 \omega + c_3 \]

where \( c, c_2 \) and \( c_3 \) are known constants.

5. A method as claimed in any one of claims 1, 2 or 3, whereby the step of estimating is characterized by the step of searching a look-up table tabulating incremental rotational speeds with predetermined values of pressure for no flow to identify the relevant value of \( p_{est} \).

6. Apparatus for estimating the flow of breathable gas to a patient from a flow generator (10) having a turbine (32), and supplying breathable gas in the administration of continuous positive airway pressure treatment or assisted respiration, including pressure measurement means (42) for measuring the pressure of gas from the flow generator (10) when operating at a known turbine rotational speed, the apparatus characterized by:

- pressure estimation means (82) for estimating the equivalent pressure of gas that would be delivered by said flow generator (10) at the known rotation speed if there was no flow to the patient; and
- processor means (20) for calculating the difference between the measured pressure and the estimated pressure to give an estimation of flow to the patient.

Patentansprüche

1. Verfahren zum Abschätzen des Flusses eines einatmungsfähigen Gases an einen Patienten (16) von einem Flussgenerator (10) mit einer Turbine (32) bei der Anwendung einer Behandlung mit einem kontinuierlichen positiven Luftwegdruck oder einer unterstützten Beatmung, mit den Schritten zum Messen des Drucks des Gases (\( p_{act} \)), das von dem Flussgenerator (10) geliefert wird, und Messen der Drehgeschwindigkeit (\( \omega \)) der Turbine (32), wobei das Verfahren durch die folgenden Schritte gekennzeichnet ist:

- Abschätzen des equivalenten Drucks eines Gases (\( p_{est} \)), welches von dem Flussgenerator (10) bei der bekannten Drehgeschwindigkeit zugeführt werden würde, wenn kein Fluss zu dem Patienten (16) vorhanden wäre; Berechnen der Differenz zwischen \( p_{est} \) und der \( p_{act} \), um eine Abschätzung über den Fluss an den Patienten (\( f_{est} \)) zu geben.

2. Verfahren nach Anspruch 1, gekennzeichnet durch den weiteren Schritt der Quadratwurzelberechnung der Flussabschätzung, um eine linearisierte Flussabschätzung zu geben.


4. Verfahren nach irgendeinem der Ansprüche 1, 2 oder 3, wobei der Schritt zum Abschätzen gekennzeichnet ist durch den Schritt zum Ausführen der folgenden Berechnung:

\[ p_{est} = c_1 \omega^2 + c_2 \omega + c_3 \]

wobei \( c, c_2 \) und \( c_3 \) bekannte Konstanten sind.

5. Verfahren nach irgendeinem der Ansprüche 1, 2 oder 3, wobei der Schritt zum Abschätzen gekennzeichnet ist, durch den weiteren Schritt der Quadratwurzelberechnung der Flussabschätzung, um eine linearierte Flussabschätzung zu geben.

6. Vorrichtung zum Abschätzen des Flusses eines einatmungsfähigen Gases an einen Patienten von einem Flussgenerator (10) mit einer Turbine (32), und Zuführen von einatmungsfähigem Gas bei der Anwendung einer Behandlung mit einem kontinuierlichen positiven Luftwegdruck oder einer unterstützten Beatmung, mit einer Druckmesseinrichtung (42) zum Messen des Drucks von Gas von dem Flussgenerator (10) bei einem Betrieb bei einer bekannten Turbinendrehgeschwindigkeit, wobei die Vorrichtung gekennzeichnet ist durch:

- eine Druckabschätzungseinrichtung (82) zum Abschätzen eines equivalenten Drucks eines Gases, das von dem Flussgenerator (10) bei der bekannten Drehgeschwindigkeit geliefert werden würde, wenn kein Fluss an den Patienten vorhanden ist, und
- eine Prozessoreinrichtung (20) zum Berechnen der Differenz zwischen dem gemessenen Druck und dem abgeschätzten Druck, um eine Abschätzung über einen Fluss an den Patienten zu geben.

Revendications

1. Procédé pour estimer la circulation d’un gaz respirable sur un patient (16) en provenance d’un générateur de circulation (10) comportant une turbine (32) au niveau de l’administration d’un traitement de
pression de voies aériennes positive continue ou d’une respiration assistée, incluant la mesure de la pression de gaz (p\text{act}) du gaz qui est délivré par le générateur de circulation (10) et la mesure de la vitesse de rotation (ω) de la turbine (32), le procédé étant caractérisé par:

l’estimation de la pression équivalente de gaz (p\text{est}) du gaz qui devrait être délivré dans le générateur de circulation (10) à la vitesse de rotation mesurée s’il n’y avait pas de circulation sur le patient (16); et

le calcul de la différence entre p\text{est} et p\text{act} afin d’obtenir une estimation de la circulation sur le patient (f\text{est}).

2. Procédé selon la revendication 1, caractérisé par
l’étape supplémentaire de prise de la racine carrée de l’estimation de circulation afin d’obtenir une estimation de circulation linéarisée.

3. Procédé selon la revendication 2, caractérisé par
l’étape supplémentaire de filtrage de ladite estimation de circulation linéarisée afin d’enlever les composantes non respiratoires.

4. Procédé selon l’une quelconque des revendications 1, 2 ou 3, dans lequel ladite étape d’estimation est caractérisée par l’étape de réalisation du calcul:

\[ p\text{est} = c_1 \omega^2 + c_2 \omega + c_3 \]

où c_1, c_2 et c_3 sont des constantes connues.

5. Procédé selon l’une quelconque des revendications 1, 2 ou 3, dans lequel l’étape d’estimation est caractérisée par l’étape de recherche dans une table de consultation qui tabule des vitesses de rotation incrémentielles avec des valeurs de pression prédéterminées pour une absence de circulation afin d’identifier la valeur pertinente de p\text{est}.

6. Appareil pour estimer la circulation d’un gaz respirable sur un patient en provenance d’un générateur de circulation (10) comportant une turbine (32) et pour appliquer un gaz respirable au niveau de l’administration d’un traitement de pression de voies aériennes positive continue ou d’une respiration assistée, incluant un moyen de mesure de pression (42) pour mesurer la pression de gaz du gaz en provenance du générateur de circulation (10) lors d’un fonctionnement à une vitesse de rotation de turbine connue, l’appareil étant caractérisé par:

un moyen d’estimation de pression (82) pour estimer la pression de gaz équivalente qui devrait être délivrée par ledit générateur de circu-