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Combined Experimental and Analytic Methods for Electrodynamic Modelling of Urinary Absorption Phenomena in a Composite Textile Medium

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Abstract. This paper uses combined experimental and analytic methods, for the development of a pioneering electrodynamic model of urinary absorption phenomena inside a composite Textile Medium. The workbench built for practical modeling needs, consists of a) an electric control source; b) ON/OFF switch; c) composite textile material (upstream *cotton* layer and downstream *luffa cylindrical* layer) with (+) and (-) wire probes; d) resistor Rs used as a collector of the electric voltage effect resulting from a urine volume Q (in ml); e) manually operated urine source (in ml); f) digital memory storage oscilloscope. For a urine volume Q inside the absorbing composite textile medium, an experimental voltage step response is applied. Then, the resulting waveform of the output voltage Us(Q) is captured and graphically monitored. On the other hand, an equivalent electronic circuit is outlined and transformed into an analytic *lead/lag dynamic model*, with parameters estimation based on data extracted from the experimental waveform of Us(Q). Finally, the proposed electrodynamic model is validated using virtual simulation results obtained under the same operating conditions in Electronic Workbench software. Therefore, the developments presented in this research paper offer a better understanding of urinary absorption phenomena in composite textile media. Furthermore, they outline new design and manufacturing opportunities of low-cost and high-quality urinary sensors for smart diapers.

Keywords. Experimental and analytic methods, urinary absorption phenomena, composite textile medium, electrodynamic model, equivalent electronic circuit, urinary sensors.

INTRODUCTION

For bioelectronic engineering educators and professionals, the urinary absorption phenomena in textile media is a growing research topic. Nowadays, a well understanding of these phenomena is very relevant to designers and manufacturers of multipurpose smart diapers, e.g., for babies even and adults affected by urinary incontinence.

The scientific operating principle of existing smart diapers is to instantaneously detect the cumulative urine volume Q (in ml) inside the diaper, then to automatically alert the wearer or any remote helping person when Q achieves a given maximum threshold.

As an implication, the most relevant element operating upstream of a urinary detecting device is a urinary sensor. Ideally, it should be designed and realized according to metrology constraints, e.g., physical state variable associated with the urine volume Q, probes input specifications, probes output specification including the physical output variable (or signal) to be captured and processed as an image of the cumulative urine volume Q inside the diaper.

Numerous types of urine sensors are available in biomedical engineering literature, each of which is based on a *specific physical effect* to be captured and processed as urine volume follower, e.g., Photoelectric (Eyall and Tikva, 2015), electric conductance (Pamela et al., 2018), electric capacitance (Ha-Duong et al., 2018), electric resistance (Pankhuri et al., 2020; Seob Lee et al., 2013; Banchajarurat et al., 2019; Fischer et al., 2016), urinary pressure level (Lai and Chang, 2019), dielectric constant (Nie et al., 2017).

However, in most of these existing solutions, the overall relationship between the cumulative urine volume Q inside the diaper and its output image Us is structurally a static operating law given by (1).

$$Us(t) = g(Q(t)) \quad \text{or} \quad Q(t) = g^{-1}\left(Us(t)\right) \tag{1}$$

Unfortunately, the validity of static models is limited to the analysis of the steady behavior of urinary absorption phenomena. Following this relevant limitation, an electric resistance-capacitance model of a urine sensor has been studied (Fischer et al., 2016).

However, its real-time prototyping requires enormous hardware resources, as well as greedy digital signal processing and monitoring tasks.

This paper combines experimental and analytical methods for better design and analysis of electrodynamic models of urinary absorbing phenomena inside a composite textile medium.

The target composite textile results from an improved version realized in previous research work (R. Nguefack et al., 2019). It consists of an *internal cotton layer* because of its better sweetness qualities and an external *luffa cylindrical layer* since it offers higher urinary absorption capacity.

The relevance of this paper relies on numerous merits, including a) simplicity of the electric voltage used as urine quantity follower; b) probes quality (symmetric morphology, minimum size, no transducer need); c) pioneering electrodynamic and virtual electronic models. The remaining sections of this paper deal with methods and tools, results and discussions, and conclusion respectively.

MATERIAL AND METHOD

Workbench diagram

The dynamic modeling and parameters estimation processes, initiated in this paper for our new type of unary sensor require suitable design methods as well as the processing and analyzing tools. Figure 1 shows the block diagram of the workbench built for conducting the whole experimental study. It consists of many parts including 1) composite textile medium for urinary absorption if any, providing an internal cotton layer and an external luffa cylindrical layer; 2) manually controllable source of urine volume (ml); 3) 02 electric wire probes with symmetric spacial morphology; 4) low power supply control voltage E(t) = 3.2 V with ON/OF switch S needed); 5) resistor Rs required for real-time access to the output voltage Us considered as the image effect of the cumulative urine volume in the textile medium; 6) oscilloscope for real-time graphical monitoring storing of Us.

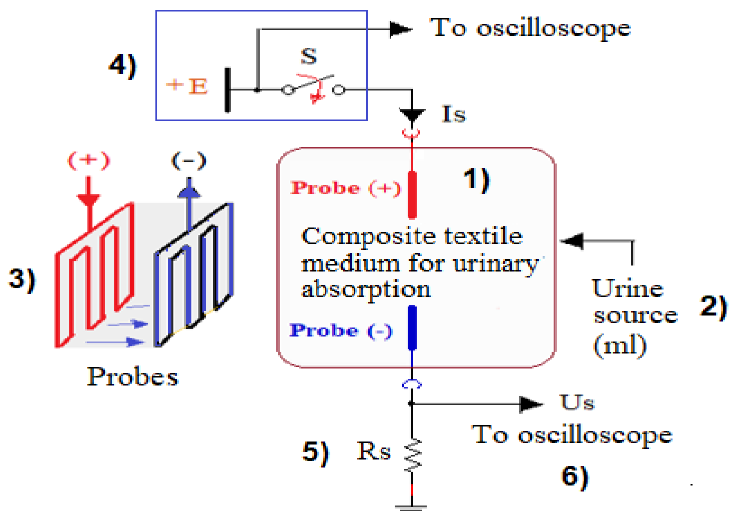


Fig.1. Block diagram of the workbench.

Experimental research method

Figure 2 shows the image of a prototyping workbench, with connected parts. From the initial dry textile medium, the first task is to turn ON the power switch S in other to start the experimental step response under E = 3.2 V, with graphical monitoring of supply voltage of E(t) and the output variable Us on the oscilloscope screen. Then the second task is to incrementally inject 20 ml of urine in the target textile medium and to run with monitoring any next experimental step response sample.

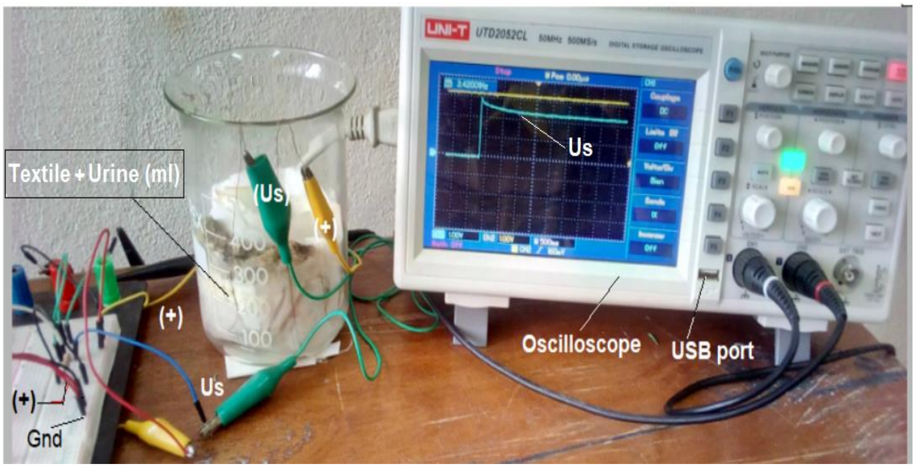
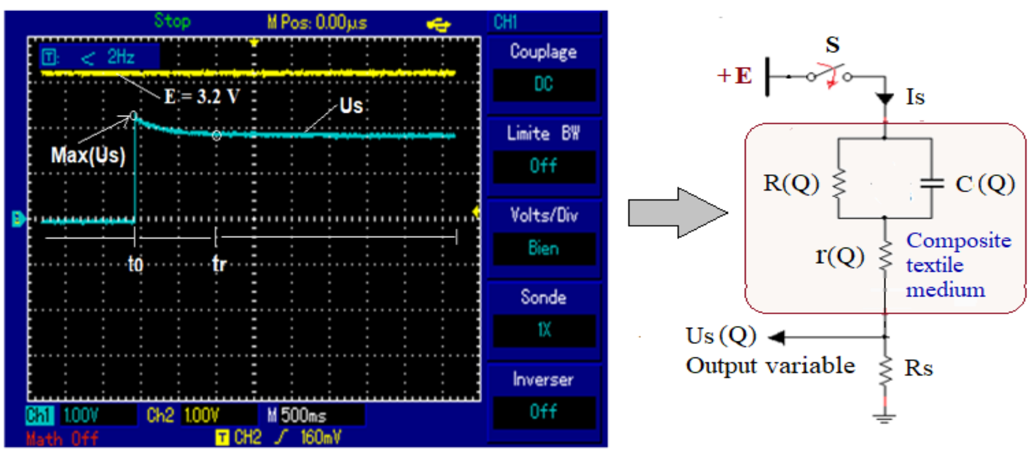


Fig. 2. Workbench of the unary detection device.

Analytic research method

Electronic diagram

At the end of the experiments, the last step is to establish an equivalent electronic model from the knowledge base extracted from the whole graphs. As a novative finding, figure 3 illustrates how the dynamic behavior of an experimental step response in figure 3a, is translated into an equivalent electronic circuit shown in figure 3b. The electrical parameters R(Q) ≡ R, C(Q) ≡ C, and r(Q) ≡ r are dictated by the total urine quantity Q (i.e. volume in ml) absorbed inside the composite textile medium.



a) Sample of experimental step response b) Equivalent electronic circuit

Fig. 3. Experimental step response and equivalent electronic circuit.

Electrodynamic models and step response

A straightforward analysis of the equivalent electronic circuit initiated in figure 3b, shows that its dynamic behavior evolves according to a first-order differential equation (2), where R(Q) ≡ R, C(Q) ≡ C, r(Q) ≡ r, and Us(Q) ≡ Us for the sake of easy notations.

$$\left(\frac{Rs+r}{Rs+r+R}\right)\frac{dUs(t)}{dt}+Us(t)-R\,C\left(\frac{Rs}{Rs+r+R}\right)\frac{dE(t)}{dt}=\left(\frac{Rs}{Rs+r+R}\right)\mathrm{E(t)} \qquad (2)$$

Note that (2) takes into account any arbitrary waveform of the voltage control source E(t). On the other hand, a rearrangement of similar terms of the Laplace transform of (2), leads to a transfer function (3) with output variable Us(t).

$$T(s)=\frac{Us(s)}{E(s)}=\left(\frac{Rs}{Rs+r+R}\right)\frac{(1+R\,C\,s)}{\left(1+\frac{(Rs+r)}{(Rs+r+R)}R\,C\,s\right)} \qquad (3)$$

As a relevant finding, (3) is structurally a *lead/lag transfer function*. In addition, for a step control voltage E(s) = E/s, the resulting U(s) is given by (4). Consequently, Us(t) given by (5) can be easily obtained from a suitable Laplace transform Table (Gille et al., 2017).

$$Us(s)=\left(\frac{Rs}{Rs+r+R}\right)\frac{(1+R\,C\,s)}{s\left(1+\frac{(Rs+r)}{(Rs+r+R)}R\,C\,s\right)}E \qquad (4)$$

$$\begin{aligned}Us(t)&=\left(\frac{Rs\;\;E}{Rs+r+R}\right)\left(1+\frac{R}{(Rs+r)}e^{-\frac{(Rs+r+R)}{(Rs+r)R\;C}(t-t0)}\right)\;\; if\;\; t>t0\\&=0\;\;\text{otherwise}\end{aligned} \qquad (5)$$

Parameters estimation

The relationship between the experimental step response in figure 3a and its analytic model given by (5), is founded on four relevant events described as follows:

1) For $t \le t0^-$, Us = 0 V in figure 3a, i.e., the witch S is initially open in figure 3b where Us = 0 V.
2) at t = t0, Us jumps from 0 V to a finite value Usm < E, i.e., the impedance C behaves across R as a short-circuit. Subsequently, then Usm can be computed from (6) given R = 0 Ω to obtain (6). It is worth noting from here that the argument Q is omitted in the right side of equations (6) to (12) for the sake of better visibility.

$$Usm(Q)=\frac{Rs}{Rs+r}E \qquad (6)$$

Therefore, r(Q) can be analytically estimated from (6) as follows, for a known Usm:

$$r(Q)=Rs\frac{(E-Usm)}{Usm} \qquad (7)$$

3) for $t \ge t0$ the step response observed in figure3a behaves as decreasing exponential law, with finite lower boundary Us(∞), i.e., the impedance 1/ (C s) in figure 3b is infinite, in which case E, R, r and Rs operate as a single mesh circuit, with steady output voltage given by:

$$Us(\infty)=\frac{Rs}{Rs+r+R}E \qquad (8)$$

Here, R can be analytically computed as follows for a known *r* value in (8):

$$R(Q) = Rs\,\frac{E}{Us(\infty)} - (Rs + r) \tag{9}$$

4) To determine C, we resort to the time response principle, denoted tr(a%), where *a(Q)* is given by:

$$a(Q) = 1 + \frac{R}{(Rs + r)}\, e^{= \frac{(Rs + r + R)}{(Rs + r)\,R\,C}\,(\text{tr(a\%)} - t0)} \tag{10}$$

Solving (10) leads to (11) and (12)

$$tr(a\%) = \frac{(Rs + R)}{(Rs + r + R)}\,R\,C\,\log\left(\frac{R}{(a-1)\,(Rs + R)}\right) \tag{11}$$

$$C\,(Q) = \frac{(Rs + r + R)}{R\,(Rs + r)\,\log\left(\dfrac{R}{a\,(Rs + r)}\right)}(tr - t0) \tag{12}$$

The virtual equivalent electronic circuit of the proposed unary sensor

A virtual simulation process in the Electronic Workbench platform requires values of data for electronic components and control signals. Without loss of generality, the case study considered here is the equivalent virtual electronic circuit presented in figure 4. It deals with the following data: E = 3.2 V, Q = 50 ml (urine volume), Rs = 10 KΩ, t0 = -1.6 s, Usm = 2.3 V, a = 102, tr (a%)= -1 s and Us (tr) = 1.9 V. The virtual ON/OFF switch S1A is useful for activating and stopping the virtual step response test. The set of simulation parameters summarized in (13) are computed according to known relationships (7), (9), and (12).

r(Q) = 3.913K, R(Q) = 3.8647 KΩ, C (Q)= 138.23 uF (13)

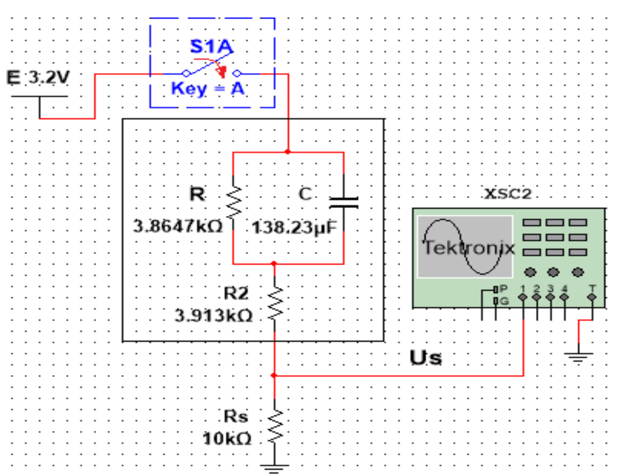
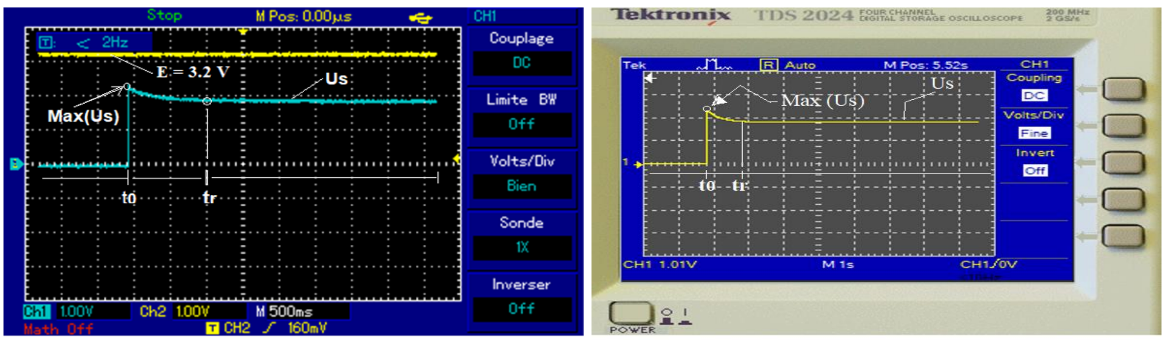


Fig. 4. A virtual electronic circuit in Electronic Workbench.

RESULTS AND DISCUSSIONS

The sample of both experimental and virtual step responses obtained when testing urinary absorbing phenomena under the same operating conditions are presented and compared in figure 5. While the same output voltage scale is used in both cases (i.e., 1 V/div), it has been necessary because of setup suitability, to use in each a specific time scale (i.e. 500 ms/div for a real oscilloscope and 1 s/div for virtual oscilloscope). As expected, both experimental and virtual behaviors are qualitatively and quantitatively identical. This last relevant finding stands for scientific validation of the rigorous *lead/lag dynamic model* of urinary absorption phenomena in composite textile media. As an implication, the combined experimental and analytical research methods initiated in this paper, are suitable for fast design and manufacturing of lower cost and high-quality urinary sensors for smart diapers.



a) Experimental (500 ms/div, 1 V/div)   b) Virtual (1s/div, 1 V/div)

Fig. 5. Experiment and virtual step responses.

CONCLUSION

The electrodynamic model initiated and well tested in this paper, has brought a better understanding of urinary absorption phenomena inside a class of composite textile media. It has been shown that the proposed pioneering model is structurally simple and consists of a *lead/lag transfer function* for any waveform of voltage control input. The output voltage Us(Q) to be instantaneously acquired and processed, is a rigorous real-time image of the cumulative urine volume (in ml) inside the absorbing textile medium. Therefore, the next relevant perspective research work is to use findings arising from this paper, for the fast design and manufacturing of digital unary detection devices for low-cost and high-quality smart diapers.

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