

PAPER • OPEN ACCESS

## A contact-based technique for measurement of membrane tension

To cite this article: Behzad Aminian *et al* 2022 *Meas. Sci. Technol.* **33** 115109

View the [article online](#) for updates and enhancements.

### You may also like

- [Cyclic behavior of superelastic SMA cable and its application in an innovative self-centering BRB](#)  
Yifei Shi, Hui Qian, Liping Kang et al.
- [Determination of the elastic properties of graphene by indentation and the validity of classical models of indentation](#)  
K M Fair, M D Arnold and M J Ford
- [Recent progress on improvement to mechanical properties of DI-BSCCO wire](#)  
K Yamazaki, T Kagiyama, M Kikuchi et al.

# A contact-based technique for measurement of membrane tension

Behzad Aminian\* , Iman Rahgozar Abadi, Sheldon Green   
and Steven Rogak 

Department of Mechanical Engineering, University of British Columbia, 2329 West Mall, Vancouver BC V6T 1Z4, Canada

E-mail: [aminian.bz@gmail.com](mailto:aminian.bz@gmail.com)

Received 24 December 2021, revised 14 June 2022

Accepted for publication 20 June 2022

Published 12 August 2022



CrossMark

## Abstract

Membranes are used widely in engineering applications, including the porous membranes in fuel cells and ventilation systems. In order to understand the mechanical behavior of the membrane, one should know the loads acting on it, including the tension applied to it during the manufacturing process. This study describes a novel contact-based method to measure the pre-tension for applications, such as membrane energy exchangers, where optical access to the membrane is limited. The method involves direct measurement of the membrane location under various pressures, using a novel probe, and inferring the pre-tension by comparing the results with theoretical models. The technique is validated by measuring the tension of membranes pre-tensioned to known values. The RMS deviation between the measured tension and the set pre-tension is  $0.55 \text{ N m}^{-1}$ , which is approximately 3% of the pre-tension used in a typical membrane energy exchanger.

Keywords: pretension measurement, membrane pretension, energy exchanger, precision displacement measurement, thin membrane tension

(Some figures may appear in colour only in the online journal)

## 1. Introduction

Membranes can be light, selectively permeable, and inexpensive, making them popular in applications including fuel cells, heating, ventilation and air conditioning (HVAC) systems, micro-electromechanical systems, and even some buildings. The membrane deformation under lateral load and the vibration characteristics of the membrane are largely a function of the membrane pre-tension. Thus, knowing the pre-tension is crucial to optimize the membrane performance and prevent structural failure [1–3]. Some researchers have tried to mitigate the issue by optimizing the spacer design [4].

In some cases, pre-tension may be inferred from details of the manufacturing process. However, the required information is unavailable in many applications. Also, the inferred pre-tension may be inaccurate since pre-tension may relax over time or due to subsequent manufacturing steps or temperature changes [5–7]. Accordingly, researchers have developed several techniques to measure the pre-tension in membranes. Tabata *et al* [7] used the load-deflection method to infer the pre-tension. This technique involves measuring the maximum deflection for different values of applied load (pressure) and obtaining the pre-tension by comparing the load-deflection curve with theoretical equations. While most researchers who adapted this method used non-contact methods to measure the deflection [4, 7, 8], Larson *et al* [1] used a linear variable differential transformer to find the membrane displacement. Recently, Merle *et al* [9] presented experimental results and analysis of a nano-indentation probe to measure membrane residual stress, and were able to obtain results, consistent with separate bulge tests. Another common approach to find the

\* Author to whom any correspondence should be addressed.



Original content from this work may be used under the terms of the [Creative Commons Attribution 4.0 licence](https://creativecommons.org/licenses/by/4.0/). Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

pre-tension relates the frequency of vibration of the membrane to its pre-tension [10]. Recently, Zheng *et al* [5] developed a technique called the ejection method. In this method, the pre-tension is inferred from rebound velocity, ejection velocity, and vibration amplitude of an ejected pellet impacted onto a membrane. Liu *et al* [6] further improved the technique by reducing the parameters and relating the pre-tension only to the maximum vibration amplitude.

Although all of these methods can measure pre-tension, they all require extensive (generally optical) access to the membrane. This paper describes a non-destructive method to measure the pre-tension of a thin membrane where optical or other access is hindered. As described in subsequent sections, at the heart of this method is a unique, contact-based technique for measuring membrane deflection with micrometer resolution.

## 2. Methodology

### 2.1. Membrane deflection theory

Figure 1 is a schematic of a membrane under uni-axial pre-tension  $T_x$  with a transverse load  $p$ .

Large deflection of a plate is given by the solution to the following nonlinear set of differential equations [11]:

$$\frac{\partial^4 F}{\partial x^4} + 2 \frac{\partial^4 F}{\partial x^2 \partial y^2} + \frac{\partial^4 F}{\partial y^4} = E \left[ \left( \frac{\partial^2 \omega}{\partial x \partial y} \right)^2 - \frac{\partial^2 \omega}{\partial x^2} \frac{\partial^2 \omega}{\partial y^2} \right] \quad (1)$$

$$\begin{aligned} \frac{\partial^4 \omega}{\partial x^4} + 2 \frac{\partial^4 \omega}{\partial x^2 \partial y^2} + \frac{\partial^4 \omega}{\partial y^4} \\ = \frac{h}{D} \left( \frac{p}{h} + \frac{\partial^2 F}{\partial y^2} \frac{\partial^2 \omega}{\partial x^2} + \frac{\partial^2 F}{\partial x^2} \frac{\partial^2 \omega}{\partial y^2} - 2 \frac{\partial^2 F}{\partial x \partial y} \frac{\partial^2 \omega}{\partial x \partial y} \right) \end{aligned} \quad (2)$$

where the flexural rigidity  $D$  and the Airy stress function  $F$  are defined by:

$$D = \frac{Eh^3}{12(1-\nu)} \quad (3)$$

$$N_x = h \frac{\partial^2 F}{\partial y^2} \quad N_y = h \frac{\partial^2 F}{\partial x^2} \quad N_{xy} = -h \frac{\partial^2 F}{\partial x \partial y} \quad (4)$$

$\omega, h, E, \nu$  denote the membrane deflection, membrane thickness, Young's modulus, and the Poisson's ratio, respectively.  $N_x, N_y, N_{xy}$  are the forces acting on the middle plane of the plate due to the in-plane stresses or applied external forces. According to [12], for a rectangular membrane with an aspect ratio  $b/a$  greater than four under uniform pressure ( $p = p_c$ ), the maximum deflection of the membrane can be found from equation (1) and (2):

$$p_c = 8 \frac{T_x}{a^2} \omega_{\max} + \frac{64}{3} \frac{Eh}{(1-\nu^2)a^4} \omega_{\max}^3 \quad (5)$$

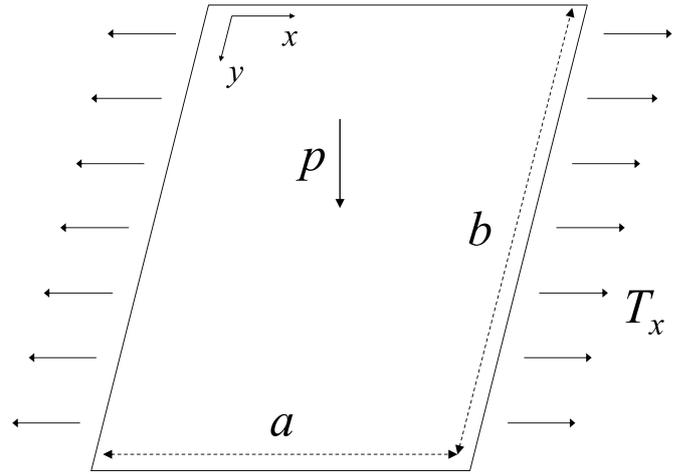


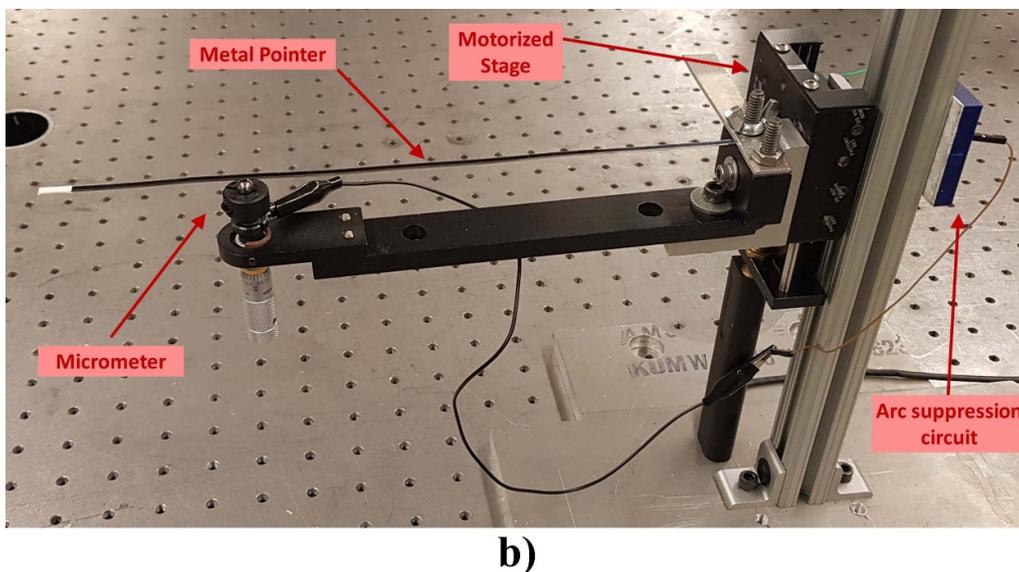
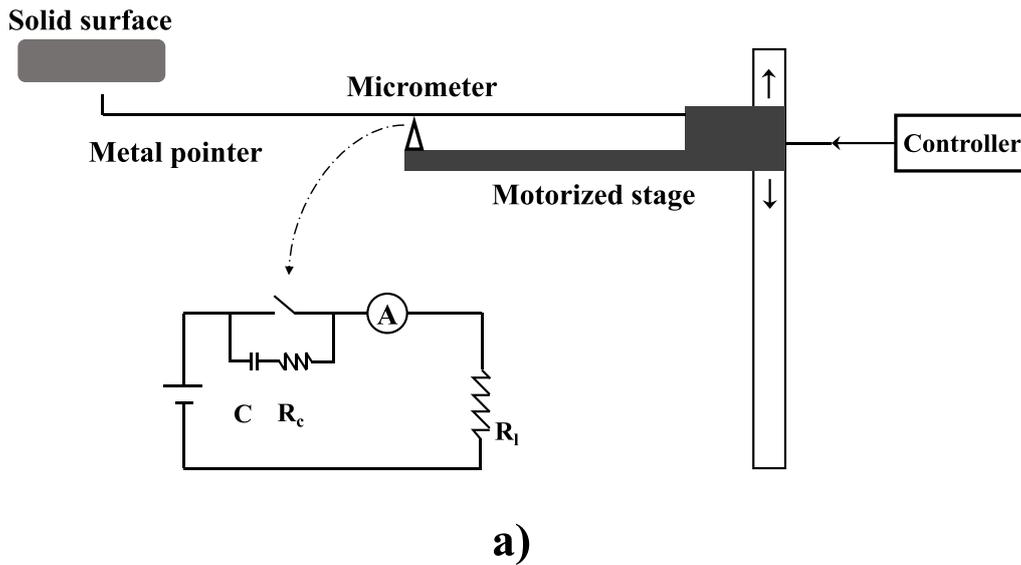
Figure 1. Schematic of a membrane under combined normal and lateral forces.

### 2.2. Deflection measurement

In section 1, several methods used to measure deflection were mentioned. However, they all require substantial access to the surface of the membrane, which in many applications may not be feasible. In this section, a novel technique for deflection measurement is described that partially addresses this limitation. Figure 2 depicts the apparatus.

The apparatus includes a high-precision motorized stage that moves vertically and is capable of moving upward and downward at a step size as small as 10 nm. Mounted on the stage is a thin metal pointer that moves with it. At a distance from the base of the motorized stage, another micrometer is attached to the stage, creating a small gap between the tip of the micrometer and the metal pointer. The gap size was set to be 1 mm in this experiment. A voltage difference is applied between the micrometer tip and the metal pointer, creating an electric circuit with an open contact. Initially, the pointer is located at a reference position a certain distance below the undeflected membrane. The motorized stage is then adjusted upwards until the physical contact between the metal pointer and the membrane deflects the pointer downwards enough to close the circuit between the pointer and the micrometer. The corresponding current is detected using an ammeter. Next, the stage is brought back to the reference position, and the procedure is repeated for different pressures applied to the membrane, and the displacement of the stage is recorded each time. The motorized stage displacement, relative to a reference, is equal to the pointer tip displacement relative to the same reference. Provided that the membrane deflection in response to the pointer load remains nearly identical throughout the experiment, this pointer tip displacement is identical to the membrane deflection.

This device provides a precise measurement of the location of the membrane, provided that the displacement of the membrane due to the applied force from the pointer is negligible. This condition will always apply if the pointer force is negligible. The approach will also be accurate, even with



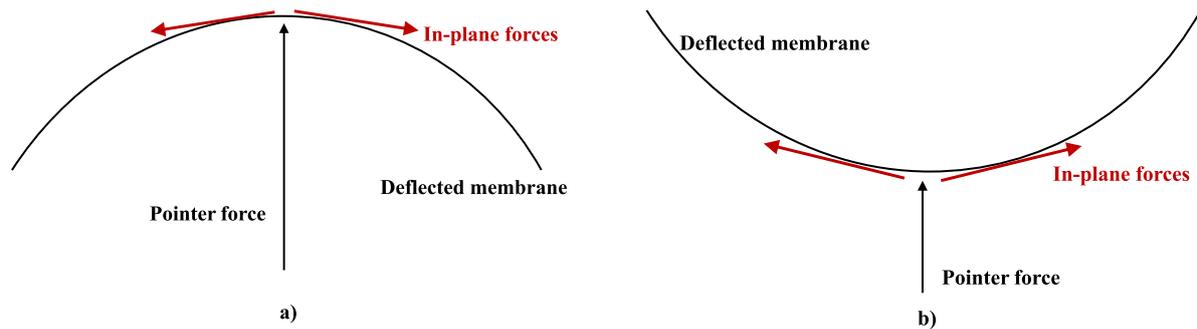
**Figure 2.** Deflection sensor (a) schematic of device (b) photograph of the sensor.

non-negligible pointer force, provided the incremental membrane displacement due to the pointer force is independent of the pressure differential across the membrane.

As mentioned above, for the experiments described here the gap size between the micrometer and the metal pointer was set to 1 mm. The gap size may be adjusted using the micrometer to smaller values, which implies less deflection at the tip of the pointer for the touch to be detected. Smaller gap sizes therefore imply that the sensor will respond to smaller forces. Since the voltage is applied across a very small gap at the micrometer, electric arcing may occur. An arc suppression circuit suggested by Bates *et al* [13] is implemented to address this issue. The circuit shown in figure 2 consists of a capacitor in series with a resistor, in parallel with the contact point. Using the arc snubber circuit, the applied voltage exists across the capacitor when the contact is open, which prevents arcing.

### 2.3. Pointer selection

This contact method for measuring location requires a small additional force to be exerted on the membrane, which may slightly deform the membrane and bias the measurement. Several factors affect the pointer force. The size, shape, and material of the pointer, the gap size between the micrometer and the pointer, and the position of the micrometer along the pointer, are all factors that contribute to this force. The design of the pointer is a trade-off between sensitivity, which requires a highly flexible pointer, and robustness. To minimize the membrane deformation caused by this pointer force, a metal pointer with low flexural rigidity was used; in this study, a 30 cm length brass pointer with a diameter of 0.8 mm is used. The micrometer is located 20 cm from the base of the pointer. The force required to deflect the pointer enough to contact the micrometer is measured to be 0.4 mN.



**Figure 3.** Pointer force relative to membrane orientation. (a) The pointer force is directed away from the center of curvature of the membrane, and (b) the pointer force is directed toward the center of curvature of the membrane.

The direction of the applied force relative to the center of membrane curvature may also be important. Figure 3 shows two possible scenarios.

In figure 3(a), the pointer force is directed away from the center of curvature of the membrane, and the tensile force acting in the membrane resists the additional deflection caused by the pointer. However, as seen in figure 3(b), when the pointer force is directed towards the center of curvature, this resistance is not present, and thus the membrane will deform more in response to the pointer force. Of course, if the force applied by the pointer is negligible, it does not matter the direction of the pointer force. Measurements in this paper are obtained using the first method (pointer force is directed away from the center of curvature). A short discussion of the effect of pointer stiffness on the measurement accuracy is given later.

### 3. Results

#### 3.1. Deflection measurement

Validation of the technique described in section 2 is carried out in two parts: validation of the deflection measurement apparatus and validation of the pre-tension inference. In this section, the accuracy of the deflection measurement apparatus is investigated by comparing its measurements with those of a Mitutoyo 543-791B Absolute Digimatic Indicator. Several rigid objects of different thicknesses were measured with both devices, and the summary of the results is tabulated in table 1. The agreement between the ‘gold standard’ indicator and the new deflection sensor is extremely good—within the reported error of the indicator.

#### 3.2. Tension measurement

In order to validate the proposed technique, one edge of a 30 cm by 20 cm piece of membrane, whose characteristics are summarized in table 2, is attached to a horizontal rod. The membrane is pre-tensioned to four different values in turn by hanging four different weights to a rod attached to the bottom of the membrane. With a prescribed pre-tension, the membrane is then clamped between the two parts of the test module shown in figure 4. The rectangular blocks clamping the

**Table 1.** Summary of thickness measurements.

Mitutoyo indicator thickness <sup>a</sup> ( $\mu\text{m}$ )	Deflection sensor	
	thickness <sup>b</sup> ( $\mu\text{m}$ )	Absolute error ( $\mu\text{m}$ )
1690	$1693 \pm 4$	3
2810	$2812 \pm 3$	2
4282	$4278 \pm 3$	-4
5628	$5625 \pm 2$	-3
7555	$7559 \pm 4$	4

<sup>a</sup> The accuracy of the digital micrometer is reported to be  $3 \mu\text{m}$ .

<sup>b</sup> Average of five measurements reported.

**Table 2.** Properties of the membrane.

Membrane material	Thickness ( $\mu\text{m}$ )	Young's modulus (MPa)	Poisson ratio
Polypropylene (Celgard 2400)	25	500 [12]	0.43

membrane are slotted so that the membrane is free to deflect upwards and downwards except at the clamped edges.

The test module is connected to a vacuum pump, which applies negative pressure on one side of the membrane. Because the seal between the membrane and the metal of the test module is imperfect, and the membrane itself has a slight porosity, a mass flow controller was used to draw a constant flow out of the concave chamber. The magnitude of this constant flow determined the magnitude of the applied pressure across the membrane, which was measured directly by the pressure gauge. As shown in figure 4, there is a  $1 \text{ cm} \times 30 \text{ cm}$  slot in the middle of the test module. For each of four different values of pre-tension, and for each of six different pressures, the deflection of the membrane at the middle of the slot was measured multiple times. Figure 5 shows a summary of the measurements.

It is inferred from figure 5 that for a given pressure differential, the higher the pre-tension, the lower the deflection. To infer the pre-tension, one fits the experimental results, with equation (5) to minimize the least-square error. Figure 6

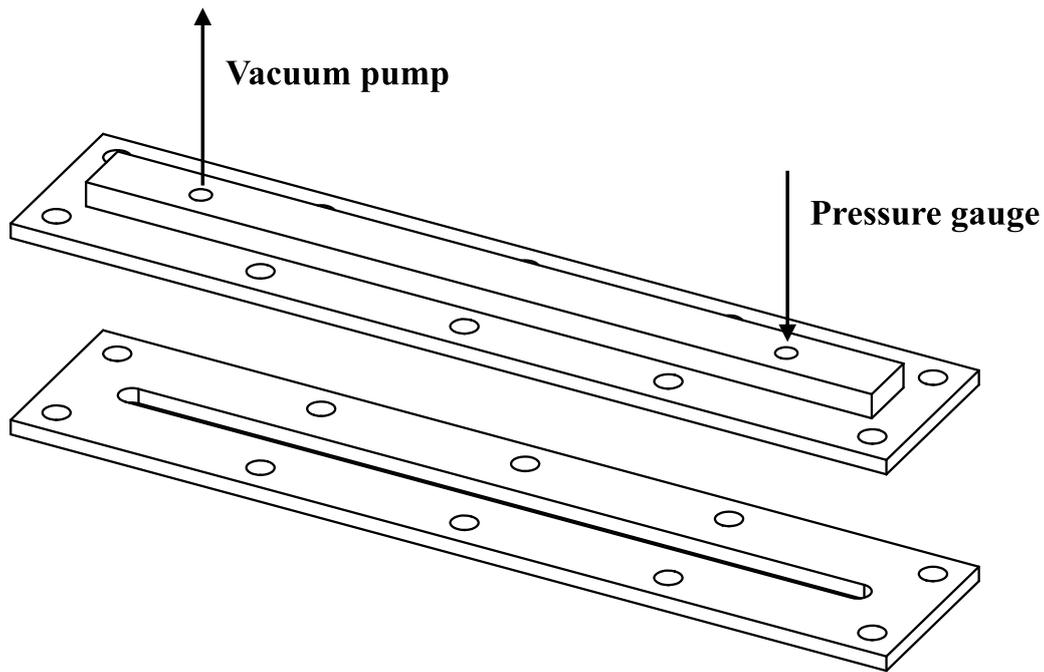


Figure 4. Schematic of the test module.

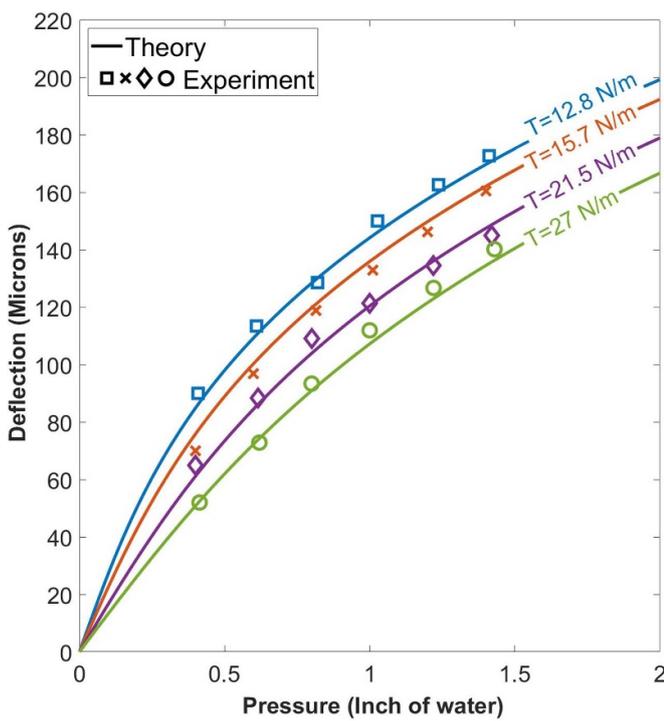


Figure 5. The load-deflection graph. The uncertainty in the pressure measurement is 0.01 inch of water and the uncertainty in the deflection measurement is 4  $\mu\text{m}$ .

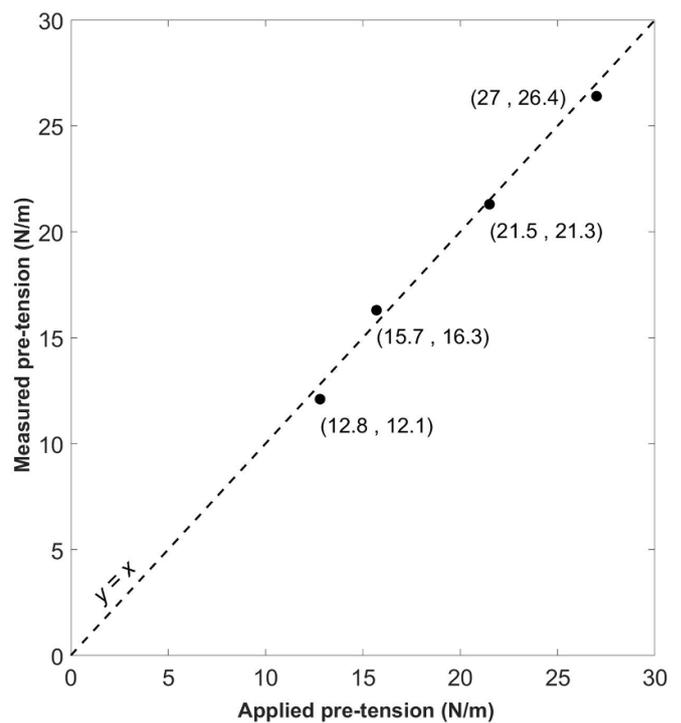


Figure 6. Comparison of reading from the technique vs experimental values.

compares the known applied pre-tension and the inferred values found by the best-fit line.

The root mean square error of the data presented in figure 6 is  $0.55 \text{ N m}^{-1}$  ( $R^2 = 0.989$ ) with no obvious bias. In a companion paper [14], we report that in a typical membrane

energy exchanger, the membrane tension is on the order of  $20 \text{ N m}^{-1}$ , and the variance in tension is a few  $\text{N m}^{-1}$ . Accordingly, the range and accuracy of this pre-tension measurement technique are suitable for its application to membrane energy exchangers.

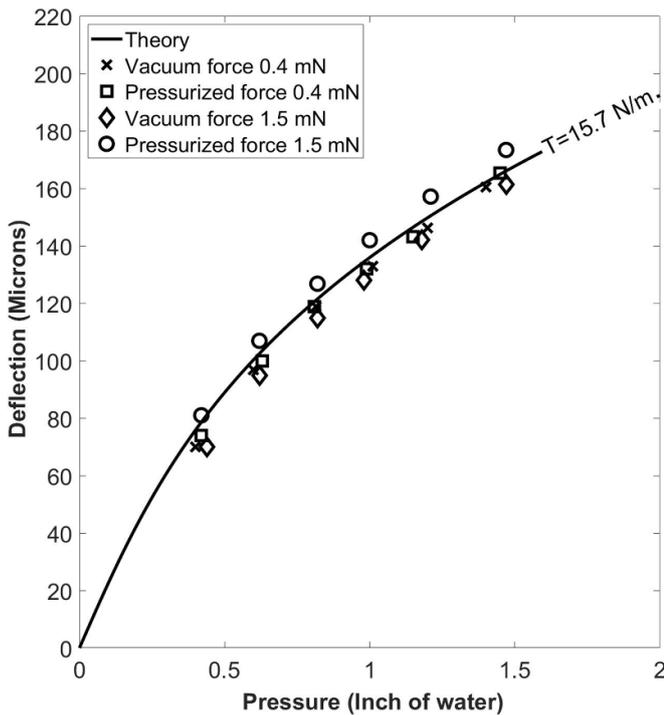


Figure 7. Effect of pointer force on the measurements.

### 3.3. Effect of pointer force

As discussed previously, measurements can be done either when the direction of the pointer force is towards the center of curvature of the membrane (membrane is at positive gauge pressure) or opposite that direction. When the pointer force is negligible, we expect no difference between the two possible methods of measurement. However, as the pointer becomes stiffer, the effect of pointer force may no longer be negligible. Generally speaking, this should increase the deviation between the measurements and the theory.

As shown in figure 7, when the pointer exerts a relatively low force, no significant difference is observed when measurements are done under the pressurized or vacuum condition. In contrast, for a higher amount of force, there is a remarkable discrepancy between the measurements. Particularly when the membrane is pressurized and the pointer force is in the counter direction of deflection.

The pointer should be sized so that the force it exerts on the membrane is small relative to other transverse forces. These transverse forces include those due to the applied pressure and pre-tension. By linearizing equation (5), it can be shown that the transverse force is on the order of  $p_c a^2$ , which for a typical applied pressure of 1 inch of water implies a transverse force of approximately 25 mN. The pointer force should therefore be small relative to 25 mN. As seen in figure 7, as the pointer force increases from 0.4 mN to 1.5 mN, its effect on the measured membrane displacement becomes significant. For the stiffer probe, the pointer force is about 6% of the pressure force at 1 inch of water, and the deviation of the deflection from the ideal case is about 5%, from inspection of figure 7. Thus, the

relative magnitude of the pointer force appears to be a reasonable indicator of the deflection error.

## 4. Conclusion

This paper documents a novel contact-based membrane deflection measurement device that does not require optical access. The device was compared with precision micrometer measurements on fixed geometries, and the agreement between the measurements was within the stated accuracy of the micrometer. The device was then used to measure the deformation under applied pressure of membranes with a known pre-tension. The RMS deviation between the applied and inferred pre-tensions is  $0.55 \text{ N m}^{-1}$ , which represents a 3% error relative to a typical membrane energy exchanger membrane. This pre-tension measurement device is thus suitable for measuring membrane pre-tension in a laboratory setting. It may also have application in the manufacturing of membrane energy exchanger cores.

## Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

## Acknowledgment

The authors appreciate the financial support provided by the Natural Sciences and Engineering Research Council of Canada and Core Energy Recovery Solutions.

## ORCID iDs

Behzad Aminian  <https://orcid.org/0000-0001-7526-4949>

Sheldon Green  <https://orcid.org/0000-0002-3819-8257>

Steven Rogak  <https://orcid.org/0000-0002-4418-517X>

## References

- [1] Larson M D, Besant R W and Simonson C J 2008 The effect of membrane deflections on flow rate in crossflow air-to-air exchangers *HVAC&R Res.* **14** 275–88
- [2] Wang C, Abdul-Rahman H, Wood L C, Mohd-Rahim F A, Zainon N and Saputri E 2015 Defects of tensioned membrane structures in the tropics *J. Perform. Constr. Facil.* **29** 04014049
- [3] Gosling P D, Bridgens B N and Zhang L 2013 Adoption of a reliability approach for membrane structure analysis *Struct. Saf.* **40** 39–50
- [4] Hereijgers J, Ottevaere H, Breugelmans T and De Malsche W 2016 Membrane deflection in a flat membrane microcontact: experimental study of spacer features *J. Membr. Sci.* **504** 153–61
- [5] Zhou-lian Z, Chang-jiang L, Wen-chuan G, Xi-shi Y, Wei-ju S, Yun-ping X and Jun L 2013 A new method—ejection method for non-destructive online monitoring of the pre-tension of building membrane structure *Struct. Control Health Monit.* **20** 445–64

- [6] Liu C J, Todd M D, Zheng Z L and Wu Y Y 2018 A non-destructive method for the pre-tension detection in membrane structures based on nonlinear vibration response to impact *Struct. Health Monit.* **17** 67–79
- [7] Tabata O, Kawahata K, Sugiyama S and Igarashi I 1989 Mechanical property measurements of thin films using load-deflection of composite rectangular membranes *Sens. Actuators* **20** 135–41
- [8] Zhanjin S and Qilin Z 2005 A study on pre-tension measurement of membrane structures *Int. J. Space Struct.* **20** 71–82
- [9] Merle B, Nicholson K S, Herbert E G and Göken M 2016 An improved method for point deflection measurements on rectangular membranes *Mater. Des.* **109** 485–91
- [10] Li D, Lai Z C, Wang Y and Zheng Z L 2020 A non-contact method for estimating the pre-tension of a rectangular membrane structure *Insight* **62** 464–70
- [11] Timoshenko S 1976 Theory of plates and shells *Theory of Plates and Shells* 2nd edn (New York: McGraw Hill) pp 378–82
- [12] Xiang Y, Chen X and Vlassak J J 2005 Plane-strain bulge test for thin films *J. Mater. Res.* **20** 2360–70
- [13] Bates C C 1966 Contact arc suppression of electromechanical relays *Electromech. Des.*
- [14] Aminian B 2022 Membrane deflection in energy exchangers *MASc Thesis* University of British Columbia (<https://doi.org/10.14288/1.0406255>)