Measurement of thoracoabdominal asynchrony: importance of sensor sensitivity to cross section deformations

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De Groote, Anne, Yves Verbandt, Manuel Paiva, and Pierre Mathys. Measurement of thoracoabdominal asynchrony: importance of sensor sensitivity to cross section deformations. J Appl Physiol 88: 1295–1302, 2000.—Discrepancies in the assessment of thoracoabdominal asynchrony are observed depending on the choice of respiratory movement sensors. We test the hypothesis that these discrepancies are due to a different dependence of the sensors on cross-sectional perimeter and area variations of the chest wall. First, we study the phase shift between perimeter and area ($\phi_{pa}$) for an elliptical model, which is deformed by sinusoidal changes of its principal axes. We show that perimeter and area vary sinusoidally in the physiological range of deformations, and we discuss how $\phi_{pa}$ depends on the ellipticity of the cross section, on the ratio of transverse and dorsoventral movement amplitudes, and on their phase difference. Second, we compute the relationship between perimeter, area, and the output of the inductive sensor, and we proceed by comparing inductive plethysmography with strain gauges for several cross section deformations. We demonstrate that both sensors can provide different phase information for identical cross section deformations and; hence, can estimate thoracoabdominal asynchrony differently. Furthermore, the complex dependence of the inductive sensor on perimeter and area warns against this sensor for the evaluation of thoracoabdominal asynchrony.

respiratory movements; strain gauges; inductive plethysmography

THORACOABDOMINAL ASYNCHRONY is known to depend on subject age (3, 8, 11), sleep stage (23), and severity of airway obstruction (2, 21, 22). This parameter is commonly measured by the phase shift between two signals representative of the thoracic and abdominal movements, according to the model of Konno and Mead (14). In these studies, strain gauges (1), inductive plethysmography (17), magnetometers (16), and linear differential transducers (14) are used without any detailed discussion of their specific characteristics. However, Heldt (10) compared the use of magnetometers, mercury-in-rubber strain gauges, and inductance plethysmograph in preterm infants. He observed that the three abdominal signals were similar, whereas the thoracic phase measurements from the magnetometers sometimes deviated from those of the strain gauges and of the inductance plethysmograph. In addition, Ross Russell and Helms (19) compared inductance plethysmographs, magnetometers, and Hall device strain gauges in children aged 1 mo to 13 yr. Although similar waveforms were observed during spontaneous tidal breathing, the phase angles sometimes varied between sensors. We have also compared signals recorded in infants by inductive plethysmography and piezoelectric strain gauges and have observed phase differences resulting in discrepancies between the measurements of thoracoabdominal asynchrony. Figure 1 shows an example of data obtained from a quietly breathing 4-mo-old baby. Thoracic and abdominal movements were simultaneously recorded by inductive sensors and piezoelectric strain gauges. The inductive belts were incorporated in a pyjama and placed respectively on the umbilicus and on the nipples. Two piezoelectric belts were superposed on the inductive belts. Figure 1, A and C, shows the signals as a function of time. Figure 1, B and D, shows each thoracic signal plotted in ordinate as a function of the corresponding abdominal signal in abscissa. This representation indicates that the thoracoabdominal asynchrony measured by strain gauges is greater than 90° (negative slope of the principal axis of the curve), whereas the asynchrony measured by inductive plethysmography is smaller than 90° (positive slope of the principal axis of the curve). The additional x-y plot of Fig. 1F shows that the abdominal signals obtained from both sensors are in phase (no hysteresis), whereas the hysteresis in Fig. 1E indicates that the thoracic signals are phase shifted. This thoracic shift accounts for the differences in thoracoabdominal phase shift.

Having observed these discrepancies, we decided to test the hypothesis that the phase shift between the electrical outputs of the two types of sensors measuring the same respiratory movements is due to a difference of sensitivity with regard to the variations of perimeter and area of the cross section. To verify this assumption, our approach consisted of three steps. First, we studied the geometrical conditions for which a phase shift occurs between variations of perimeter and area, and then we compared inductive plethysmography and strain gauges for the measurement of cross section deformations and for the evaluation of thoracoabdominal asynchrony. Inductive plethysmography is conven-
tionally chosen to measure area variations, whereas strain gauges are known to be sensitive only to perimeter changes. The analysis of the sensitivity of the inductive sensor to perimeter and area variations is based on the work of Martinot-Lagarde et al. (15), who have analyzed the inductance-area and inductance-perimeter dependence on the cross section and belt characteristics. Their aim was to evaluate the accuracy of inductive plethysmography for measurement of area and perimeter changes. We have extended their work to evaluate the accuracy of thoracoabdominal asynchrony measurements obtained by respiratory inductive plethysmography, for which inconsistent results have been found, as shown in Fig. 1.

METHODS

Basic cross section and deformations. Figure 2A shows the model used to compute the thoracic and abdominal cross sections: an ellipse with minor and major axes corresponding to the dorsoventral and transverse directions, respectively. One point of the ellipse is fixed to simulate the spine, while the ellipse center moves during the respiratory cycle. Figure 2B shows a mathematical equivalent model, which is obtained by fixing the ellipse center. Respiratory movements are simulated by sinusoidal variations of each semiaxis \( x(t) \) and \( y(t) \) as follows (Fig. 2C)

\[
x(t) = x_m + X \sin (2\pi ft) \\
y(t) = y_m + Y \sin (2\pi ft + \varphi)
\]

where \( X \) and \( Y \) are the motion amplitudes, \( x_m \) and \( y_m \) are the mean values of the semiaxes, \( f \) is the respiratory frequency, \( t \) is time, and \( \varphi \) is the asynchrony between lateral and ventral movements. The ellipticity ratio is defined as \( y(t)/x(t) \).

The area (A) and perimeter (P) of the ellipse are given by

\[
A(t) = \pi x(t)y(t)
\]

and

\[
P(t) = 4y(t)E[1 - (x(t)/y(t))^2]
\]

where \( E() \) is the elliptic integral of the second kind, calculated between 0 and \( \pi/2 \). Detailed computations are given in APPENDIX A.

Sensitivity analysis. Strain gauges generate a voltage when submitted to mechanical strain. Respiratory motion sensors based on this principle can be, for example, obtained by including a piezoelectric film, sensitive to elongation, in relatively stiff belts surrounding the thorax or the abdomen. For these sensors, the strain sensitivity of the transducer combined with the belt elasticity determines the perimeter measurement. Inductive plethysmography uses thoracic and abdominal belts fitted with zigzag-shaped wires, which enable some extension. The loops are characterized by their self-inductance and are placed in an oscillator circuit, the frequency of which is modulated by the variations of the

Fig. 1. Comparison of thoracic (Tho) and abdominal (Abd) respiratory movements measured simultaneously in a 4-mo-old baby by means of piezoelectric strain gauges (S) and inductive plethysmography (I). A and C: thoracic and abdominal signals as a function of time. B and D: thoracic signal as a function of corresponding abdominal signal. E and F: inductive signal as a function of corresponding signal obtained from strain gauge. au, Arbitrary units.

Fig. 2. A: elliptical model of thoracic and abdominal cross sections during breathing. Principal axes represent transverse and dorsoventral diameters. Fixed point corresponds to spine (●). Three different cross sections are represented. B: mathematical model equivalent to A, with center of ellipse considered fixed. \( X \) and \( Y \) are amplitudes of principal semiaxis \( x(t) \) and \( y(t) \); \( f \), time moves. C: simulation of respiratory movements by sinusoidal variations of each semiaxis \( x(t) \) and \( y(t) \), with amplitudes \( X \) and \( Y \) around mean values \( x_m \) and \( y_m \). \( f \), respiratory frequency. \( \varphi \), Phase shift between \( x \) and \( y \) movements.

inductance due to the respiratory movements. Demodulation can be obtained by a conventional Respitrace (Respitrace, Ardsley, NY), which provides an output voltage proportional to the self-inductance. The dependence of this sensor on perimeter and area is complex, as can be seen in Eq. 4, which gives the expression for the self-inductance (L) in the case of a simple circular loop of radius \( a \), made with a wire of cross-sectional radius \( r \) (9, 15)

\[
L = \mu_0 a \left( \ln \left( \frac{8a}{r} \right) - \frac{7}{4} \right)
\]  

Eq. 4

The self-inductance of a wire of constant length uniformly distributed in sinusoidal shape around a plane elliptical cross section (principal axes \( 2x_m \) and \( 2y_m \)) has been computed by using the Neumann coefficients (APPENDIX B). The inductance-area and inductance-perimeter relationships were calculated in the physiological range for infants (6, 13, 18).

RESULTS

Perimeter-area phase shift. We show in APPENDIX A that the perimeter and area time functions \( \{P(t) \text{ and } A(t)\} \) are sinusoidal when the amplitudes \( X \) and \( Y \) are small with respect to the mean principal axes \( x_m \) and \( y_m \). Furthermore, the phase shift of \( P(t) \) and \( A(t) \), with respect to the phase of the original movements, depend on three parameters: the mean ellipticity ratio \( y_m/x_m \), the amplitude ratio \( Y/X \), and the phase shift \( \phi \) between transverse and dorsoventral movements. Hence, the phase shift between \( P(t) \) and \( A(t) \) (\( \Phi_{PA} \)) also depends on these parameters. Figure 3 shows \( \Phi_{PA} \) in a semilogarithmic representation, as a function of the movement amplitude ratio \( Y/X = 0.1 \) to 10 for different phase shifts between \( x \) and \( y \) movements (\( \phi = 60^\circ, 100^\circ, 160^\circ, 170^\circ, 180^\circ \)). Figure 3A is plotted for the mean ellipticity ratio \( y_m/x_m = 0.5 \), whereas Fig. 3B corresponds to \( y_m/x_m = 0.7 \). In Fig. 3, \( \Phi_{PA} \) equal to 0° implies that the perimeter and the area variations of the cross section are in phase. When subjected to this type of cross section deformation, all sensors, whether they are sensitive to perimeter or to area, will generate equivalent output. Hence, in this case, a detailed analysis of sensor sensitivity is superfluous. In contrast, \( \Phi_{PA} \) equal to 180° corresponds to the extreme situation in which the perimeter and area

![Fig. 3. Perimeter-area phase shift (\( \Phi_{PA} \)) calculated on an elliptical cross section, semiaxes of which vary sinusoidally, as a function of movement amplitude ratio \( Y/X \) on a logarithmic scale, for different mean ellipticity ratios (A: \( y_m/x_m = 0.5 \); B: \( y_m/x_m = 0.7 \)) and different phase shifts (\( \phi \)) between movements in \( x \) and \( y \) directions.](http://jap.physiology.org/)
modulations have an opposite phase. In this case, very different phase measurements can be expected from sensors with different sensitivity to variations of perimeter and area.

Sensitivity of the inductive sensors. The self-inductance of a 650-mm-long wire, with eight sinusoidal zigzags, was calculated by discretization of the Neumann equation. We assumed wires with an elliptical layout defined by ratios $y_m/x_m$ equal to 1, 0.9, 0.8, 0.7, 0.6, or 0.5, respectively. For each ellipticity, we considered five different sizes of cross section, providing an area ranging from 110 to 150 cm$^2$. As described by Martinot-Lagarde et al. (15), we obtained a set of inductance-area (Fig. 4A) and inductance-perimeter (Fig. 4B) curves, depending on the section shape. The same information is shown in Fig. 5, in which we plotted isoshape ($y_m/x_m$) and isoinductance ($L$) in a perimeter-area plane.

$P(t)$ and $A(t)$ are sinusoidal for the section deformations considered in this paper (APPENDIX A). Therefore, the respiratory movements can be described by means of elliptical trajectories in the perimeter-area representation. Table 1 details the sets of parameters ($x_m, y_m, X, Y, \psi$) used for the different simulations illustrated in Fig. 6. Three cases are possible, corresponding to $\Phi_{PA} = 0^\circ, 0^\circ < \Phi_{PA} < 180^\circ$, and $\Phi_{PA} = 180^\circ$, respectively. Figure 6A shows an example of the first case: $P(t)$ and $A(t)$ are in phase ($\Phi_{PA} = 0^\circ$). The curve describing the

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**Fig. 4.** Inductance-area ($L-A$; A) and inductance-perimeter ($L-P$; B) relationships for a 650-mm sinusoidal wire (8 zigzags) placed on different elliptical sections defined by their ellipticity $y_m/x_m$.

**Fig. 5.** Perimeter-area ($P-A$) relationships obtained from Fig. 4. Curves of isoshape and of isoinductance have been drawn on a major grid (bold lines) and a minor grid. Bold rectangle delimits region examined more closely in Fig. 6.
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section deformations in infants could fulfill these condi-
tions. In fact, we observed the deformations of thoracic
sections in three sleeping infants and found that, in
half of the recordings, Y/X ranged from 0.5 to 1.5 in
conjunction with \( \psi > 10^\circ \). Our preliminary results
indicate that complex cross sections do occur and that
they depend on the craniocaudal position of the studied
section. The section deformations probably depend both
on the chest compliance and on the respiratory pattern.
Hence, a significant phase shift between perimeter and
area is expected to be observed in babies younger than 1
yr, showing high compliance (12), or in obstructive

cross section deformation is a straight line with posi-
tive slope (in fact, a degenerate ellipse). The second case,
where \( 0^\circ < \Phi_{PA} < 180^\circ \), is illustrated in Fig. 6B. The
curve describing the cross section deformation is an
ellipse. The curve hysteresis and the sign of the slope of
the major axis indicate the phase difference for \( P(t) \) and
\( A(t) \). Figure 6C shows three examples of the third case,
where \( P(t) \) and \( A(t) \) have an opposite phase (\( \Phi_{PA} =
180^\circ \)). The curves describing the cross section deforma-
tions are straight lines with negative slopes (degener-
et ellipses). The difference between these three curves
lies in their slopes, which are respectively equal, greater
than, or smaller than the slope of the isoinductance
curves. In fact, the absolute slope of the perimeter-area
curve varies from infinity to zero when Y/X increases
within the range defining \( \Phi_{PA} = 180^\circ \) (see Fig. 3).

**DISCUSSION**

Conditions inducing a phase shift between perimeter
and area variations. Figure 3 defines the conditions on
shape and deformation of the elliptical section that
induce a phase shift between perimeter and area. It shows
that to obtain a \( \Phi_{PA} \) different from zero, there
must be a significant (>60°) phase shift between lateral
and dorsoventral movements. In addition, the ratio of
lateral and dorsoventral movement amplitudes must
fall within a well-defined range, which increases when
ellipticity decreases. Actually, the more the cross sec-
tion tends to a circle \( (y_m/x_m \) tends to 1), the narrower is
the range of movement amplitude Y/X for which \( \Phi_{PA} \)
is significant and the less we risk obtaining a \( \Phi_{PA} \) differ-
ent from zero, because \( \Phi_{PA} \) is smaller for equivalent \( \psi \)
and Y/X. The implications of these three conditions will
now be analyzed in detail.

To observe a significant value of \( \Phi_{PA} \), lateral and
dorsoventral movements must be desynchronized and
the ratio of movement amplitudes must be inside an
interval extending from Y/X = \( y_m/x_m \) to a value between
1 and 2. This implies well-defined complex deforma-
tions of the cross section. Up to now, only a few studies
have measured in detail the respiratory movements.
Furthermore, all were achieved on healthy adult sub-
jects (4, 5, 7, 20). Nevertheless, some preliminary
unpublished results obtained in our laboratory by
means of a three-dimensional optoelectronic motion
 analyzer (Elite, BTS, Milan, Italy) indicate that some
section deformations in infants could fulfill these condi-
tions. In fact, we observed the deformations of thoracic
sections in three sleeping infants and found that, in
half of the recordings, Y/X ranged from 0.5 to 1.5 in
conjunction with \( \psi > 10^\circ \). Our preliminary results
indicate that complex cross sections do occur and that
they depend on the craniocaudal position of the studied
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<th>( y_m )</th>
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\( \Phi_{PA} \), phase shift between perimeter and area; \( y_m \) and \( x_m \), mean values of semiaxes; \( Y \) and \( X \), motion amplitudes; \( \psi \), asynchrony between lateral and ventral movements.

**Fig. 6.** Set of trajectories in P-A representation (detail of Fig. 5) due to respiratory movements. Because \( P(t) \) and \( A(t) \) are sinusoidal, the corresponding curve is elliptical. Depending on \( \Phi_{PA} \) (A: \( \Phi_{PA} = 0^\circ \); B: \( 0^\circ < \Phi_{PA} < 180^\circ \); C: \( \Phi_{PA} = 180^\circ \)), the curve can be a straight line with positive slope, an ellipse, or a straight line with negative slope. Values chosen for each curve are given in Table 1.
pathologies where even more complex respiratory patterns may occur.

Previous studies (13, 18) have shown that the thoracic cross section is more circular in early infancy and becomes more elliptical with aging. Results obtained by Openshaw et al. (18) indicate a thoracic index (dorsoven- tral diameter divided by transverse diameter) that evolves from 0.8 at 3 mo to 0.6 at 1 yr. A stabilization of the thoracic index occurs by the age of 2–3 yr. Hence, the risk of being in a physiological situation in which \( \Phi_{PA} \) is different from 0 will increase from birth to 2–3 yr.

Sensitivity of the inductive sensor and its influence on phase measurement. From the slope of the isoinductance curves of Fig. 5, we can see the simultaneous dependence of the inductive sensor on the perimeter and on the area. Curves parallel to the perimeter axis (infinite slope) would indicate that, whatever the perim- eter, an inductive sensor depends selectively on area variations. On the other hand, curves parallel to the area axis (slope equal to 0) would indicate that, whatever the area, only the perimeter determines the value of \( L \). Because the isoinductance curves of Fig. 5 have a finite nonzero slope, an intrinsic, simultaneous dependence on the perimeter and on the area is always present in the inductive sensor. This difference of sensitivity can be of great importance during the evaluation of thoracoabdominal asynchrony if a non- zero \( \Phi_{PA} \) is present (Fig. 6).

In Fig. 6A, the curve describing the cross section deformation is a straight line with positive slope (case of a degenerate ellipse): \( P(t) \) and \( A(t) \) are in phase (\( \Phi_{PA} = 0^\circ \)). This line does not a priori coincide with an isoshape curve, depending on whether the deformation occurs at constant ellipticity or not. Because this curve is closed for one respiratory cycle and shows no hysteresis, each isoinductance curve is intersected twice, for the same values of \( P(t) \) and \( A(t) \). Hence, the inductance evolution will be in phase with \( P(t) \) and \( A(t) \). In this case, the inductive sensor measures perimeter and area variations without distinction; strain gauges and inductive sensors provide the same phase information.

Figure 6B shows an example for which the curve describing the cross section deformation is an ellipse, the width and major-axis slope of which indicate a phase difference for \( P(t) \) and \( A(t) \) (\( 0^\circ < \Phi_{PA} < 180^\circ \)). This section deformation implies necessarily a variable section shape as shown by the evolution in the isoshape network. The curve is always closed during a respiratory cycle but shows hysteresis: each isoinductance is intersected twice at points with different (perimeter, area) values. Hence, the inductive signal is shifted by comparison to \( P(t) \) and \( A(t) \). In this case, the inductive sensor does not measure selectively either the perimeter or the area. The signal obtained from a strain gauge, which measures only the perimeter, is phase shifted with respect to the inductive sensor. Hence, the respiratory phase information obtained from the two sensors is different.

Figure 6C shows an example in which the curves describing the cross section deformations are straight lines with negative slopes. This indicates a phase inversion between \( P(t) \) and \( A(t) \) (\( \Phi_{PA} = 180^\circ \)). The section deformation implies necessarily a variable section shape. Depending on whether the absolute slope is greater than, equal to, or smaller than the isoinductance slope, \( L \) will be, respectively, in phase with perimeter (while in phase inversion with area), constant during the deformation, or in phase with area (while in phase inversion with perimeter). These three cases are illustrated by the three different curves in Fig. 6C. Hence, depending on the situation, the inductive sensor measures either perimeter or area. In these extreme situations, the signal obtained from a strain gauge can be in opposition with the inductive signal, inducing a completely different phase interpretation. Nevertheless, it must be noted that the amplitude of the inductive signal (measured by the number of isoinductance curves crossed by the curve describing the cross section deformation) is smaller in Fig. 6C than in Fig. 6, A and B.

This study shows that, if the perimeter and the area variations of the cross section are phase-shifted (\( \Phi_{PA} \neq 0^\circ \)), the respiratory phase information obtained by means of inductive sensors or strain gauges is different. This can explain the discrepancies observed in the example of Fig. 1. In Fig. 1A, the signals obtained from the strain gauges are by definition proportional to the perimeter of the thoracic and abdominal cross sections. In Fig. 1C, the inductive signals are proportional to the wire inductance of the thoracic and abdominal sensor. Hence, the x-y representations \( T_ho-Tho_s \) and \( Abd-I-Abd_S \) in Fig. 1, E and F, are equivalent to \( L_{Tho-P_{Tho}} \) and \( L_{Abd-P_{Abd}} \), respectively. They can be drawn in an L-P representation similar to Fig. 4B. As the \( T_ho-Tho_s \) curve shows hysteresis, its drawing in the perimeter-area representation of Fig. 5 corresponds to the simulated curve with hysteresis (case 2 of Fig. 6B). This implies a complex deformation of the section, which accounts for the phase shift observed between signals from sensors sensitive in a different way to perimeter and area. On the other hand, the \( Abd-I-Abd_S \) curve shows no hysteresis; it corresponds to the situation of Fig. 6A. There is a uniform deformation of section, which explains the identical phase information obtained from the sensors.

Implications on thoracoabdominal asynchrony measurement. In the study of thoracoabdominal asynchrony, an additional degree of complexity is introduced because two different cross sections are monitored and their deformations are compared. Couples of inductive sensors and couples of strain gauges can provide different thoracoabdominal asynchrony information because of their respective sensitivity on perimeter and area and the respective deformations of the thoracic and abdominal cross sections. It is difficult to estimate the probability of this situation occurring and the magnitude of the discrepancy. At present, we can only speculate that the discrepancies between inductive sensors and strain gauges will most probably be observed in infants (<1 yr) because of their high thoracic compliance and in obstructive pathologies because these involve complex respiratory patterns. Because induct-
tive sensors are sensitive to both perimeter and area variations in a complex way and because even two identical belts can be subjected to different thoracic and abdominal cross section deformations, we recommend that caution should be taken when this type of sensor is used for the evaluation of thoracoabdominal asynchrony in young infants and in patients with obstructive patterns.

In summary, we tested the hypothesis that commonly used sensors for measuring chest and abdominal wall motion can show a different sensitivity to perimeter and area, which could explain the observed differences in the measurement of thoracoabdominal asynchrony. After defining the conditions that induce a phase shift between perimeter and area variations, we demonstrated the possibility of experimental situations for which strain gauges and inductive belts provide different phase information for identical cross section deformations and thus differently evaluate thoracoabdominal asynchrony. From the complex dependence of the inductive sensors on perimeter and area, we conclude that caution should be taken when this kind of sensor is used for the measurement of thoracoabdominal asynchrony.

APPENDIX A

Area and perimeter calculations for the section deformation described in Fig. 2 are given below.

Area calculation. Introducing the sinusoidal movements (Eq. 2) in the area (A) formula (Eq. 3), we get

$$A(t) = \pi x(t)y(t) = \pi x_m y_m[1 + X/X_m \sin (2\pi ft)][1 + Y/Y_m \sin (2\pi ft + \varphi)]$$

When $X/X_m << 1$ and $Y/Y_m << 1$, neglecting the second order terms, it yields

$$\Delta A(t) = \pi Y y_m[X \sin (2\pi ft) + X/Y_m y_m \sin (2\pi ft + \varphi)]$$

$$= C_1 \sin (2\pi ft + \Phi_\lambda)$$

where $\Delta A(t)$ represents the area variations. $C_1$ is a constant, and $\Phi_\lambda$ is the phase shift of $A(t)$ with respect to the phase of the original movement $x(t)$. $\Phi_\lambda$ depends on $X/Y$, $X_mY_m$, and $\varphi$.

Hence, it can be seen that $A(t)$ varies sinusoidally around the mean area ($A_m$)

$$A(t) = A_m + C_1 \sin (2\pi ft + \Phi_\lambda)$$

Perimeter calculation. Introducing the sinusoidal movements (Eq. 2) in the perimeter (P) formula (Eq. 4), we get

$$P(t) = 4y(t)[1 - (x(t)/y(t))^2]$$

$$= 4y(t)[1 - (X/y_m)^2][1 + X/X_m \sin (2\pi ft)][1 + Y/Y_m \sin (2\pi ft + \varphi)]$$

$E(\ )$ is the elliptic integral of the second kind, calculated between 0 and $\pi/2$, given by

$$E(m) = \int_0^{\pi/2} \sqrt{1 - m \sin^2(\theta)} \, d\theta$$

APPENDIX B

Calculation of self-inductance by the Neumann coefficients is illustrated below.

The self-inductance (L) of a closed lead (length $\lambda$) with circular cross section of negligible radius ($r$) compared with the curvature radius ($R$) along the axis of the loop ($r << R$) is obtained by using the Neumann coefficients ($N_{ji}$) with some approximations (9, 15). These coefficients allow the calculation of the mutual inductance between the leads $j$ and $i$ ($M_{ji}$)

$$N_{ji} = \frac{\mu_0}{4\pi} \left( \oint_{C_j} \oint_{C_i} \frac{dl_i \cdot dl_j}{R_{ij}} \right) = M_{ji}$$

The self-inductance is obtained when the leads $j$ and $i$ are merged

$$L = \frac{\mu_0}{4\pi} \left( \oint_{C_j} \oint_{C_i} \frac{dl_i \cdot dl_j}{R_{ij}} \right)$$

Here, $dl_i$ and $dl_j$ represent length elements of wire, separated by a distance $R_{ij}$. The integrals must be calculated on
the outline of the lead. Figure 7 shows the sinusoidal belt used in this work to model the inductive sensor.

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