

# Evaluation of the Energy Harvestable from an Airless Tire Equipped with Piezoelectric Bimorphs on the Lamellar Spokes

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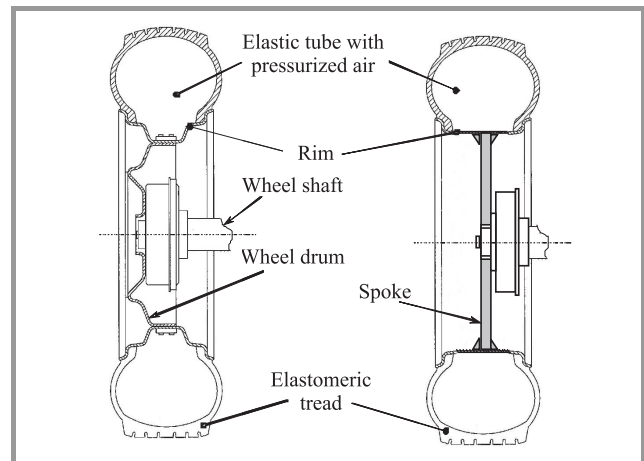
**Abstract**—In this work, one evaluates the electrical power generated by an airless tire equipped with piezoelectric bimorphs on both lateral surfaces of the radially distributed lamellar spokes. Such sheet-like spokes are hinged both toward the wheel drum at the inner annular band, and toward the wheel tread at the outer annular band. Since the hinged spokes are able to transmit tension forces but unable to transmit compression forces, bending and buckling of the spokes occur in the region of contact between the tire and the road. Models for the rolling friction of the airless tire, for the bending and buckling deformation of the spokes, and for the electrical power generated by the airless tire are suggested. Variation of the curvature radii and bending deformations for the spokes in the region of contact with the road are illustrated for various values of the rolling friction coefficient and spoke length. Then, variation of the generated electrical power versus the length of contact is obtained for various travel speeds of the vehicle. One observes that the generated electrical power increases at augmentation of the rolling friction coefficient, spoke length and travel speed. Although the obtained electrical power for the proposed harvesting system is relatively modest, it is not depending on the road roughness, i.e. harvesting becomes possible even on smooth roads, such as highway surfaces.

**Keywords**—airless tire, bending and buckling, energy harvesting, generated electrical power, piezoelectric bimorph, spoke.

## 1. Introduction

Wheels are considered as a major source of excitation in motor vehicles [1], the excitation frequency increasing with the vehicle speed and decreasing with the wavelength of the road roughness. While a vehicle is resting or running, its supporting tires receive on their hubs (wheels) a load proportional to the gross mass of the vehicle, and then tires transfer the load to the ground (road, railway, etc.) as a contact pressure [2]. Tires should endure such contact pressure, to provide for a buffering function, i.e., to absorb the energy of shock and vibrations produced by the rough road, and also to maintain a proper quasi-circular shape. Pneumatic tires utilize the internal inflation pressure as mean of carrying the load. Such tire is inflated through a valve, which is positioned either on an

inner elastic tube, or on a rim in the case of a “tubeless” type (Fig. 1). The most serious problem of air-filled tires is the puncturing, which leads to a flat tire or even to an explosion at high traveling speeds. This might cause severe traffic accidents.

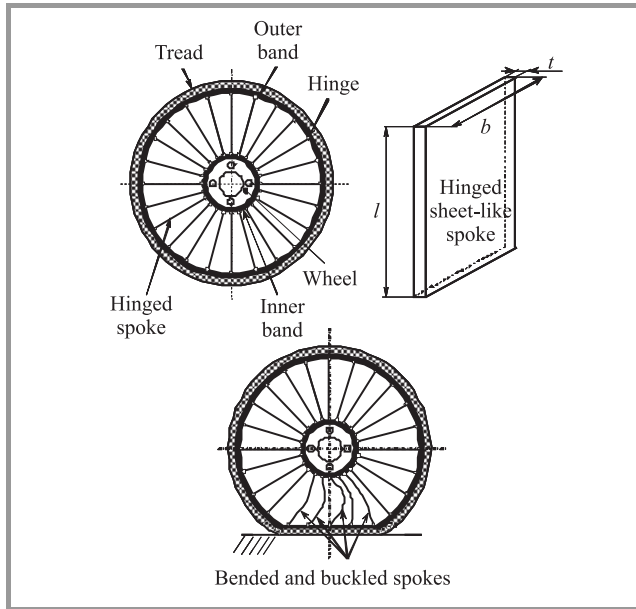


**Fig. 1.** Schematic view of a classical pneumatic tire with the rim supported by a wheel drum (left side) or radially distributed spokes (right side).

Standard pneumatic tires [3], [4] are also susceptible to depressurization due to the air leakage at the valve as well as around of the wheel rim, and due to the oxygen absorption into the elastomeric part. Loss of pressure causes the tire to flatten in the area where the load is applied, producing a larger contact area of the tire with the ground with every revolution. This leads to increased friction and wear at the contact region with the road, i.e., to larger loss of energy. On the other hand, increased bending and buckling deformations in the contact region produces temperature augmentation and consequently, quicker degradation of the tire.

In order to avoid the disadvantages of standard pneumatic tires (puncturing and depressurization), non-pneumatic or airless tires were developed [3]–[6]. A non-pneumatic or airless tire does not utilize the internal inflation pressure to carry the load. Instead, load is supported by solid struc-

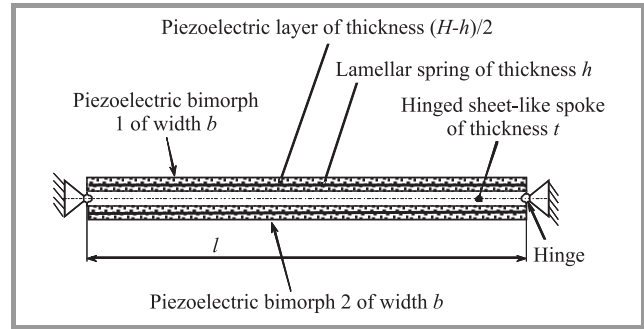
tural elements (tread, annular bands, spokes, etc.). Some of these elements are working in compression and the other in tension. Principles for carrying the load include the column, arch, and buttress for distribution of load which have been largely used for building cathedrals, monuments, roads, bridges, etc.



**Fig. 2.** Structure of an airless tire (upper left side), geometry of the hinged sheet-like spokes (upper right side), and bending or buckling deformation of the spokes on the contact surface with the road (lower part).

A non-pneumatic tire is usually made of five parts bonded together (see the upper left side of Fig. 2): the hub or wheel having an axis of rotation, a spoke section, an annular outer band that surrounds the spoke section, an elastomeric tread portion that surrounds the outer band and contacts the ground, and a mounting inner band at the radial inner end of the web spokes [5]. The mounting band anchors the tire to the hub or wheel. Elastomeric tread has an annular shape and a thickness of about 10 mm. It integrally covers the annular band and has a grooved pattern on the outer circumferential face similar to that of a classical pneumatic tire. Sometimes a side-cover (not illustrated in Fig. 2) is used to keep the tire spokes from filling with mud and dirt thereby maintaining wheel balance and ride smoothness. Usually the lamellar or sheet-like spokes (upper right side of the Fig. 2), uniformly distributed in the radial direction are employed; they may be axially aligned, or may be oblique to the tire axis. In order to obtain an almost uniform pressure on the contact surface with the road, sheet-like spokes are hinged both toward the wheel drum at the inner annular band, and toward the wheel tread at the outer annular band. Since the hinged spokes are able to transmit tension forces but unable to transmit compression forces [5], [6], bending and buckling of the spokes occur in the region of contact between the tire and the road (see the lower part of the Fig. 2).

In this work, the electrical power generated by an airless tire equipped with piezoelectric bimorphs of thickness  $H = 0.43$  mm is evaluated. Bimorphs are bonded on both lateral surfaces of the lamellar spokes (Fig. 3). Electrical



**Fig. 3.** Structure and dimensions of an energy harvesting spoke coated with piezoelectric bimorphs.

power is obtained due to the cyclical bending or buckling of the piezoelectric bimorphs together with the associated spoke in the region of contact with the road [7]. Such piezoelectric bimorph [8]–[10] consists of a lamellar metallic spring of thickness  $h = 0.1$  mm whose both lateral surfaces are coated by a piezoelectric ceramic material, as for example, M1 piezoelectric ceramic supplied by Fuji Ceramics Ltd. [11]. First, in this theoretical investigation, models for the rolling friction of the airless tire, for the bending and buckling deformation of the spokes, and for the electrical power generated by the airless tire are suggested. Then, variation of the curvature radii and bending deformations of the spokes, on the contact surface with the road, is investigated for various values of the rolling friction coefficient and spoke length. In the end, variation of the generated electrical power versus the length of contact is investigated for various travel speeds of the vehicle.

## 2. Model of the Rolling Friction for an Airless Tire

Figure 4 illustrates the behavior of a tire with a rotational direction, the rolling being represented in idealized form on a flat underlying surface, on which a flattened contact area is produced. Length  $2C$  of the contact area is measured from the entry into the contact region up to the exit from contact area; it depends on the tire characteristics, on the wheel load, the tire pressure, the driving state (longitudinal and/or lateral forces), the travel speed and the road status (dry, wet, etc.). Thus, the tire has a bending deformation from a quasi-circular shape to a flattened shape at the entry into the contact area, and a bending deformation from a flattened shape to a quasi-circular shape at the exit from the contact area. At entry into and exit from the flat contact with the ground, the centrifugal acceleration suddenly changes, and the repeatedly flexed tread increases its temperature.

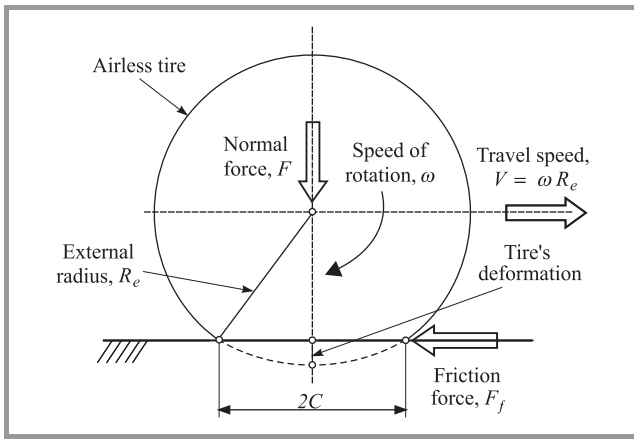


Fig. 4. Model of rolling friction for an airless tire.

Rolling friction coefficient  $\mu_r$  of an airless tire is defined as the ratio of the friction force  $F_f$  and the normal force  $F_n$  (Fig. 4):

$$\mu_r = \frac{F_f}{F} = \frac{C}{\sqrt{R_e^2 - C^2}} = \frac{\bar{C}}{\sqrt{1 - \bar{C}^2}}; \quad \bar{C} = \frac{C}{R_e}. \quad (1)$$

Here, the dimensionless contact length  $\bar{C} = \frac{C}{R_e}$  is taken as the ratio of the contact length  $2C$  to external diameter  $2R_e$  of the airless tire. One observes that  $\mu_r \cong \bar{C}$  for usual values of the dimensionless contact length ( $\bar{C} = 0.2 - 0.4$ ).

### 3. Model for the Bending or Buckling Deformation of the Spoke of an Airless Tire

As Fig. 5 illustrates, the lamellar spoke of length  $l = R_e - R_i$  occurs as planar in the upper part of the tire, between the entry into and the exit from the flat contact region with the ground ( $x = \pm C$ ). Since the hinged spokes are able to transmit tension forces in the upper part of the tire, but unable to transmit compression forces in the region of contact between the tire and the road, the following assumption can be made concerning the bending or buckling deformation of the spokes: length of the deformed (curved) spoke equals the length  $l = R_e(1 - \bar{R}_i)$  of the spoke before bending or buckling, as shown on lower part in Fig. 5.

In such circumstances, variation of the spoke dimensionless deformation  $\delta$  versus the dimensionless coordinate  $\bar{x}$  taken along the contact region can be expressed by the following relationship:

$$\bar{\delta} = \frac{\delta}{R_e} = \bar{\rho} - \sqrt{\bar{\rho}^2 - 0.25 \left( \sqrt{1 - \bar{C}^2 + \bar{x}^2} - \bar{R}_i \right)^2}. \quad (2)$$

Here, the dimensionless curvature radius  $\bar{\rho}$  of the spoke, the dimensionless coordinate  $\bar{x}$  and the dimensionless radius of the wheel drum are defined as follows:

$$\bar{\rho} = \frac{\rho}{R_e}; \quad \bar{x} = \frac{x}{R_e}; \quad \bar{R}_i = \frac{R_i}{R_e}. \quad (3)$$

Dimensionless curvature radius  $\bar{\rho}$  of the spoke is computed by numerically solving the following equation, derived on the basis of the above-mentioned assumption concerning the length of the bended spoke:

$$\sin \frac{1 - \bar{R}_i}{2\bar{\rho}} = \frac{\sqrt{1 - \bar{C}^2 + \bar{x}^2} - \bar{R}_i}{2\bar{\rho}}. \quad (4)$$

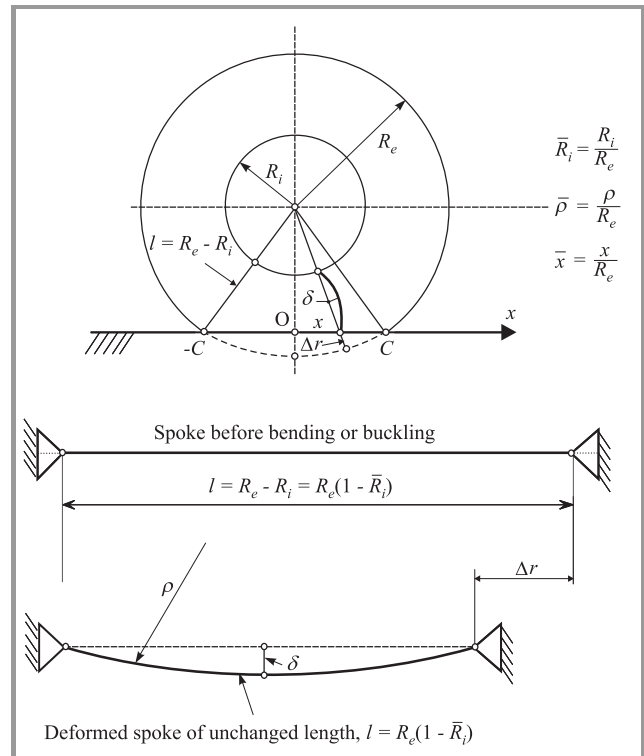


Fig. 5. Model for the bending or buckling deformation of the spoke in the contact region of the airless tire with the ground.

### 4. Model of the Electrical Energy Generated by Lamellar Spokes Coated by Piezoelectric Bimorphs

For a four wheels vehicle equipped with airless tires employing lamellar spokes coated by piezoelectric bimorphs, as already illustrated in Figs. 2 and 3, the generated electrical power can be calculated as follows [11], [12]:

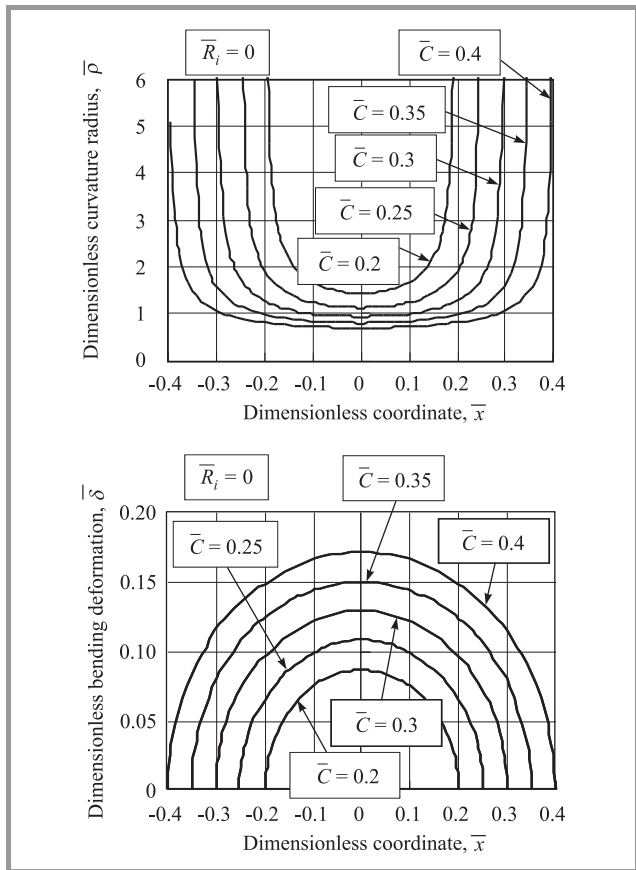
$$P = \frac{9}{8\pi^2} k_{31}^2 \Gamma \frac{1 - \bar{R}_i}{1 + \frac{h}{H}} nbHV^3 J; \quad J = \int_0^{\bar{C}} \bar{\delta}^2(\bar{x}) d\bar{x}. \quad (5)$$

Here,  $V$  is the traveling velocity of the vehicle,  $n$  is the number of spokes included into the web connecting the inner and outer annular bands of the airless tire,  $\Gamma$  is the density of the ceramic material of the employed piezoelectric bimorph,  $k_{31}$  is the global electromechanical constant of the piezoelectric bimorph, and the integral  $J$  represents the mean potential energy of deformation of the bended

spoke. The generated electrical power varies proportionally with the density of the piezoelectric ceramic material, the number of spokes, the spoke length  $\frac{l}{R_e} = 1 - \bar{R}_i$  expressed in dimensionless form, the mean potential energy of deformation of the bended spoke  $J$ , the width  $b$  of the spoke, and the thickness  $H$  of the bimorphs. On the other hand, the generated electrical energy is proportional to the second power of the global electromechanical constant of the piezoelectric bimorph, and to the third power of the traveling velocity. In conclusion, usage of piezoelectric ceramic materials with high values for density and electromechanical constant is desirable. Additionally, the generated electrical power maximizes for nil thickness of the lamellar spring of the piezoelectric bimorph ( $h = 0$ ), which means that the piezoelectric ceramic material should be directly applied on the lamellar spoke.

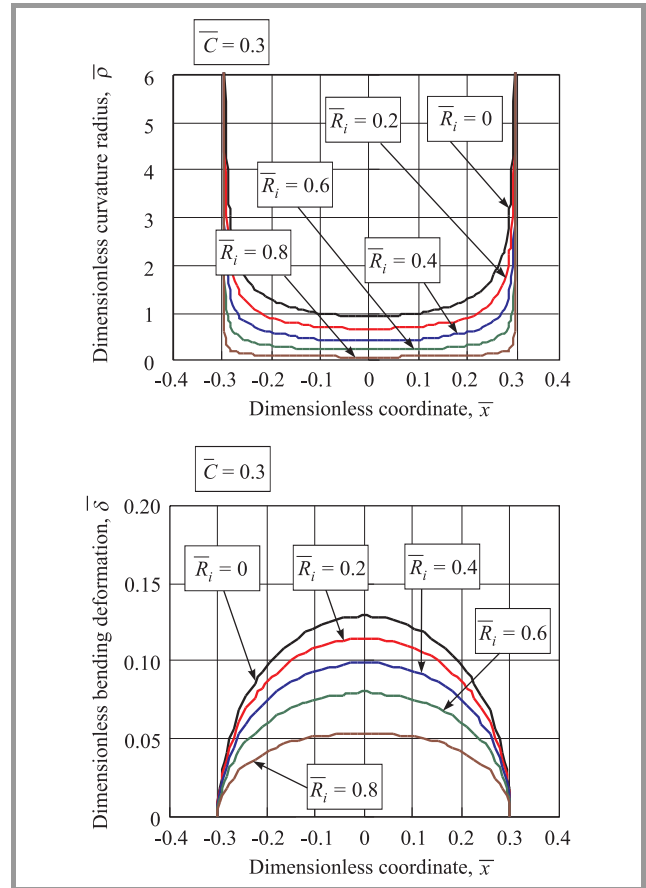
### 5. Numerical Results and Discussions

Figure 6 illustrates the variation of the dimensionless curvature radius  $\bar{\rho}$  of the spoke (upper part) and the dimensionless bending deformation  $\bar{\delta}$  of the spoke (lower part) versus the dimensionless coordinate  $\bar{x}$  for the longest spoke



**Fig. 6.** Variation of the dimensionless curvature radius (upper part) and the dimensionless bending or buckling deformation (lower part) of the spoke versus the dimensionless coordinate along the contact region, for the longest spoke and various values of the rolling friction coefficient.

( $R_i = 0$ ) and for various values of the dimensionless contact length  $\bar{C} = 0.2, 0.25, 0.3, 0.35$  and  $0.4$ . Additionally, Fig. 7 presents the variation of the dimensionless curvature radius  $\bar{\rho}$  of the spoke (upper part) and the dimensionless bending deformation  $\bar{\delta}$  of the spoke (lower part) versus the dimensionless coordinate  $\bar{x}$  for the most probable dimensionless length of the contact region  $\bar{C} = 0.3$ , i.e., the most probable rolling friction coefficient  $\mu_r$  of about  $0.3$ , and various dimensionless radii of the wheel drum:  $\bar{R}_i = 0, 0.2, 0.4, 0.6$  and  $0.8$ .



**Fig. 7.** Variation of the dimensionless curvature radius (upper part) and the dimensionless bending or buckling deformation (lower part) of the spoke versus the dimensionless coordinate along the contact region, for the most probable value of the rolling friction coefficient and various values of the dimensionless radius of the wheel drum.

From Figs. 6 and 7 one observes that at the entry into and the exit from the flat contact region with the ground ( $x = \pm C$ ) the curvature radius of the spoke tends to infinity and the bending or buckling deformation of the spoke tends to zero. This can be explained by the fact that at these locations ( $x = \pm C$ ) the curved spoke regains its planar shape, see the lower part of the Fig. 2. Additionally, at augmentation of the rolling friction coefficient or length of the contact region (Fig. 6), as well as at augmentation of the length of the spoke (Fig. 7), the maximum value of the bending deformation and also the variation rate of the bending deformation increases. Since the electrical power



generation varies proportionally to both the maximum value and the variation rate of the bending deformation, one expects also increased efficiency of the proposed harvesting system.

Based on the results presented in the lower part of Figs. 6 and 7, one calculates the integral  $J$ , i.e. the mean potential energy of deformation of the bended spoke (Table 1).

Table 1

Variation of the integral  $J$  (mean potential energy of deformation of the bended spoke) for various values of the dimensionless length of contact and radii of the wheel drum

$J \cdot 10^{-4}$	$\bar{R}_i$				
	0.0	0.2	0.4	0.6	0.8
$\bar{C}$	0.0	0.2	0.4	0.6	0.8
0.20	9.98	7.96	5.94	3.92	1.90
0.25	19.45	15.34	11.52	7.57	3.61
0.30	33.52	26.65	19.76	12.88	5.99
0.35	53.08	42.08	31.08	20.06	9.06
0.40	78.96	62.40	45.83	29.26	10.93

Next, Fig. 8 illustrates the variation of the generated electrical power versus the dimensionless contact length for various values of the traveling speed  $V = 20, 40, 60, 80$  and  $100$  km/h, for a total number of spokes  $n = 24$ , for

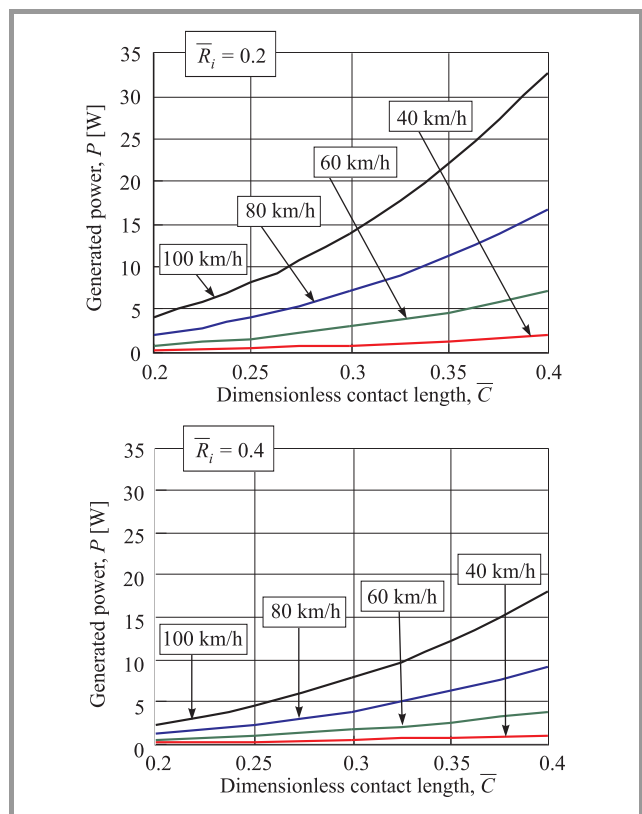


Fig. 8. Variation of the generated electrical power versus the dimensionless contact length for various traveling velocities of the vehicle and the most probable values of the dimensionless radii of the wheel drum, i.e. 0.2 (upper part) and 0.4 (lower part).

a width of the spoke  $b = 0.1$  m, for a M1 piezoelectric ceramic material, supplied by Fuji Ceramics Ltd. [11], having a density equal to  $\Gamma = 7,600$  kg/m<sup>3</sup>, and a global electromechanical coefficient equal to  $k_{31} = 6.5$ , and for the most probable values of the dimensionless radii of the wheel drum, i.e.,  $\bar{R} = 0.2$  (upper part of the Fig. 8) and  $\bar{R} = 0.4$  (lower part of the Fig. 8). Numerical results presented in Fig. 8 confirm that the generated electrical power increases at the augmentation of the spoke length and traveling speed of the vehicle. Although the obtained electrical power for the proposed harvesting system is relatively modest (a few tens of watts), it is not depending on the roughness of the road, i.e., harvesting becomes possible even on smooth traveling roads, such as highway surfaces.

### 6. Conclusion

In this work, the electrical power generated by an airless tire equipped with piezoelectric bimorphs on both lateral surfaces of the radially distributed lamellar spokes was evaluated. Models for the rolling friction of the airless tire, for the bending and buckling deformation of the spokes, and for the electrical power generated by the airless tire were suggested. Variation of the curvature radii and bending deformations for the spokes in the region of contact with the road were illustrated for various values of the rolling friction coefficient and spoke length. Then, variation of the generated electrical power versus the length of contact was obtained for various travel speeds of the vehicle. Based on the theoretical analysis performed and the numerical results obtained, the following conclusions were inferred:

- Generated electrical power varies proportionally with the density of the piezoelectric ceramic material, the number of spokes, the mean potential energy of deformation of the bended spoke, the length and width of the spokes, and the thickness of the piezoelectric bimorphs bonded on the lateral surfaces of the spokes.
- Electrical energy is proportional to the second power of the global electromechanical constant of the piezoelectric bimorph, and to the third power of the traveling velocity of the vehicle. Thus, usage of piezoelectric ceramic materials with high values for density and electromechanical constant is desirable.
- Electrical power maximizes for nil thickness of the lamellar spring of the piezoelectric bimorph, which means that the piezoelectric ceramic material should be directly applied on the lamellar spoke.
- Electrical power increases at augmentation of the rolling friction coefficient, i.e., at augmentation of the length of the contact region between the airless tire and the ground. This behavior was explained by the increased maximum value of the bending deformation and also by the increased variation rate of the bending deformation in the contact region.

- Although the obtained electrical power for the proposed harvesting system is relatively modest (a few tens of watts), it is not depending on the roughness of the road, i.e., harvesting becomes possible even on smooth roads, such as highway surfaces.

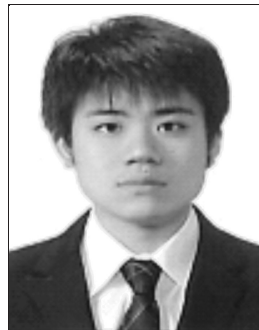
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