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COMPARISON OF TWO FINITE ELEMENT MODELS OF BRISTLES OF GUTTER BRUSHES FOR STREET SWEEPING

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Abstract: This paper models a bristle of a gutter brush for road sweeping, by means of two finite element models. In one of the models, displacement and rotation boundary conditions are applied to an end of the bristle, so that it follows a certain circular path under a given function of time. In the other model, the same end of the bristle is totally constrained, and inertia loads are applied so that they simulate the motion given by the path and function of the first model. The results of both models are validated, analysed, and compared. They indicate that their accuracy with respect to the degree of freedom results is acceptable. However, regarding force and moment results, the accuracy of the first model strongly depends on the number of straight lines used to approximate the circular path. The accuracy may be very low, mainly due to the modelling of damping. Appropriate values for the time step and integration time step are found so that both models produce reliable results. When these values are used, they provide practically the same results. It is concluded that the model that applies inertia loads may be more appropriate, because the modelling of damping may be more realistic and because much less computational resources are required.

Keywords: dynamic FEM; damping; inertia loads; displacement boundary conditions; friction

1 INTRODUCTION

This work is related to a research into the characteristics and performance of gutter brushes. These are cup-shaped brushes of road sweepers that sweep the debris that is located in the gutter of the road. The study of this brush is of certain interest, as about 80% of the road debris is found in the gutter [1,2]. Fig. 1 depicts a gutter brush of a street sweeper. It comprises one or more rows of clusters of bristles attached at an angle ϕ (bristle mount angle) relative to the mounting board normal.

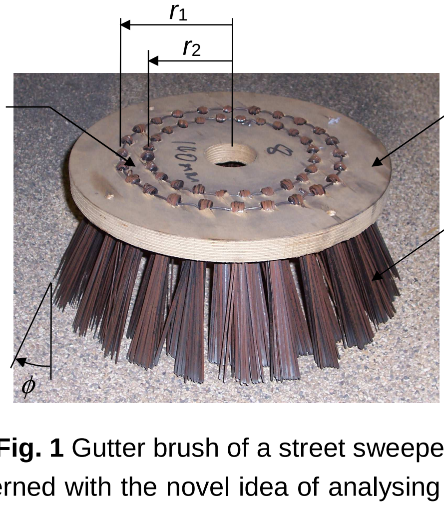


Fig. 1 Gutter brush of a street sweeper

In particular, the research is concerned with the novel idea of analysing whether oscillations superimposed onto the rotation of the gutter brush are of any value for increasing sweeping effectiveness. Therefore, in order to study brush characteristics, a *dynamic* Finite Element Model (FEM) is considered. A dynamic model of a cup-like, oscillatory brush has been developed; this model entails a transient nonlinear structural 3-D analysis involving contact, and it is described in a previous work [3]. In this model, the clamped ends of the bristles are fixed (the brush mounting board is modelled as a stationary body); therefore, in order to simulate brush motion, inertia loads are applied. In conjunction to this, the road surface has to be rotated and translated to obtain the relative movement between brush and road.

In this paper, the results of applying the model referred to above are compared with those a FEM in which the clamped end of the bristle is rotated about the brush axis. The circular path followed by the bristle top end is approximated by a large number of straight lines.

The outline of the paper is as follows. Section 2 presents the main parameters and characteristics of the model. Section 3 provides the results of the validation of the model; this process enabled to obtain the friction coefficients for concrete surface-road interaction. Section 4 presents the comparison of the results of the two models; the results of sensitivity analyses and the validation of the models are also included. Finally, Section 5 concludes the paper.

2 DESCRIPTION OF THE MODEL AND METHODOLOGY

The model that applies inertia loads has been described in detail in a previous work [3]; therefore, only the basic characteristics and the main parameters are provided here. The geometric parameters of the gutter brush that is modelled are given in Table 1. Some of these parameters are illustrated in Fig. 1. Regarding the bristle mount orientation angle, it controls the deflection of the bristle. If γ= 0 (cutting brush), the bristle cross section is orientated such that the bristle mainly deflects in the brush radial direction. If γ = 90° (flicking brush), it deflects backwards, i.e., tangentially and opposite to the bristle sweeping direction.

Table 1 Brush geometric parameters used in the models

Geometric parameter	Symbol	Value
Bristle mount orientation angle	γ	0 (cutting brush)
Bristle length	l_b	240 mm
Mount radius	r	112.5 mm
Bristle breadth	t_1	2 mm
Bristle width	t_2	0.5 mm
Bristle mount angle	ϕ	26°
Number of mount radii	n_r	1

The bristles are modelled as 3-D quadratic beams. For bristle-road interaction, rigid-to-flexible contact is assumed: a contact element is attached to the bristle tip (flexible) and a target element to the road surface (rigid). Regarding friction modelling, an exponential friction function is used [4]:

$$\mu = \mu_k + (\mu_s - \mu_k)e^{-c_v|v|}, \tag{1}$$

where μ_k is the kinetic friction coefficient, μ_s is the static friction coefficient, v is the relative velocity, and c_v is the decay coefficient.

As the modelling of an oscillatory brush requires a dynamic analysis, load steps (loads and boundary conditions) are applied every Time Step (TS), δt. Through these steps, the motions of the brush and the surface are modelled. Two load cases are studied in this work. In the first case, the displacement load case (DispLC), nodal displacements and rotations are prescribed to the top (clamped) nodes, to simulate brush rotation, and displacements are applied to the surface, to simulate sweeper speed. In the second case, the inertia load case (InerLC), the motion of the brush is simulated by applying inertia forces, but the bristle top remains fixed, and the surface is translated and rotated. For the DispLC, this is illustrated in Fig. 2(a), where, Δs and $\Delta\theta$ are the clamped node displacement and rotation, respectively, and Δx is the surface displacement (see also Fig. 6). For the InerLC (Fig. 2(b)), the surface is rotated and displaced through a pilot node in order to model the relative motion between bristle and surface (see also Fig. 7). The inertia forces applied are the centrifugal and tangential forces, related to the variable rotational speed, as well as the Coriolis effects. A disadvantage of the DispLC is that the circular path followed by the clamped end is approximated by a polygon of many sides (each side corresponds to a ramped function); this approximation may lead to inaccuracies, as discussed later; therefore, δt has to be sufficiently small (see sensitivity analyses in Section 4). Similarly, the TSs are divided into integration time steps (ITSs), δt_{ITS}; the ITS has to be sufficiently small to obtain the required accuracy when applying the dynamic equilibrium equations. In both models, gravity is applied as an inertial force.

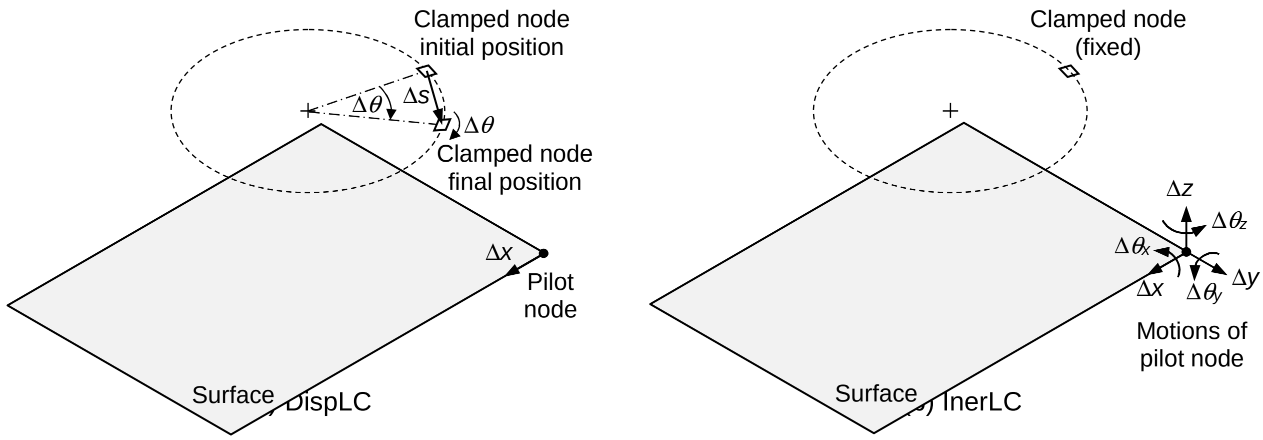


Fig. 2 Displacements and rotations prescribed to the clamped node and the surface pilot node

An oscillatory brush rotates at a variable angular speed $\omega(t)$. Two $\omega(t)$ functions are considered. The VAP function, which was devised by the authors to produce small brush angular accelerations and is given by [5]

$$\omega(t) = \omega_m + \frac{2\omega_a}{1-b} h_1(t)\left(1 - b\, e^{\frac{1-b}{b}[2h_2(t)-1]}\right), \tag{2}$$

where

$$h_1(t) = \frac{1}{\pi}\arcsin(\sin(2\pi f t)) \tag{3}$$

and

$$h_2(t) = \frac{1}{\pi}\arcsin\{\sin[\arccos(\cos(2\pi f t))]\}. \tag{4}$$

In these equations, ω_m and ω_a are the mean angular speed and alternating angular speed, respectively, f is the frequency of speed oscillation, t is time, and b is a number between 0 and 1 that controls the shape of the angular speed curve; the closer the parameter to zero, the smaller the maximum angular acceleration, but the speed curve becomes less smooth.

The second function is a sinusoidal function

$$\omega(t) = \omega_m + \omega_a \sin 2\pi f t\,. \tag{5}$$

As mentioned before, the variable angular speed produces centrifugal and tangential forces. For the InerLC, these are applied by means of the ANSYS commands ‘‘OMEGA’’ and ‘‘DOMEGA,’’ respectively. Besides, the Coriolis effects are applied through the command ‘‘CORIOLIS’’; further details are given in Ref. [3]. In the DispLC, $\omega(t)$ is integrated in order to obtain the angular function $\theta(t)$; this is used to prescribe the nodal displacements ($r \cdot \Delta\theta(t)$) and rotations ($\Delta\theta(t)$).

Regarding damping, Rayleigh damping is assumed; this is a form of viscous damping, which leads to linear equations of motion. In this damping model, damping forces are proportional to the velocity of the element, and the damping matrix **C** is in turn proportional to a linear combination of mass and stiffness dependent damping:

$$\mathbf{C} = \alpha_D \mathbf{M} + \beta_D \mathbf{K}\,, \tag{6}$$

where **M** is the mass matrix, **K** is the stiffness matrix, α_D is the mass proportional damping coefficient, and β_D is the stiffness proportional damping coefficient.

3 VALIDATION OF THE MODEL AND FRICTION COEFFICIENTS

The FEMs have been validated by comparing the results of the two load cases dealt with (see Section 4) and by comparing the modelling results with those obtained experimentally by Peel [6] for a horizontal brush (i.e., a brush with its mounting board parallel to the surface). The comparison with experimental data enabled to obtain the friction parameters (Eq. 1) for road-bristle interaction.

As reported by Peel [6], the contact between a bristle and a rough surface exhibits stick-slip friction cycles. This is because an irregularity of the road surface may stop the tip for some time until it climbs up the irregularity. However, in the Finite Element (FE) analyses performed, no stick-slip friction cycles are exhibited, because the surface is modelled as a totally flat surface; therefore, equivalent friction coefficients are determined. This is not entirely satisfactory, but the complexities of modelling a rough surface are avoided.

The validation and process of determining the friction coefficients are provided in a previous work; the results suggest that the FEM is valid, as the experimental points are fitted appropriately by the FE results [7]. The validation process yields: μ_k = 0.27, μ_s = 0.70, and c_v = 0.40 s/m for the cutting brush (γ = 0) [7]. These values are obtained by a best fit (Eq. 1) of three points (see Fig. 3), which were obtained by finding suitable values of the friction coefficients for three brush rotational speeds (60, 100, and 140 rpm).

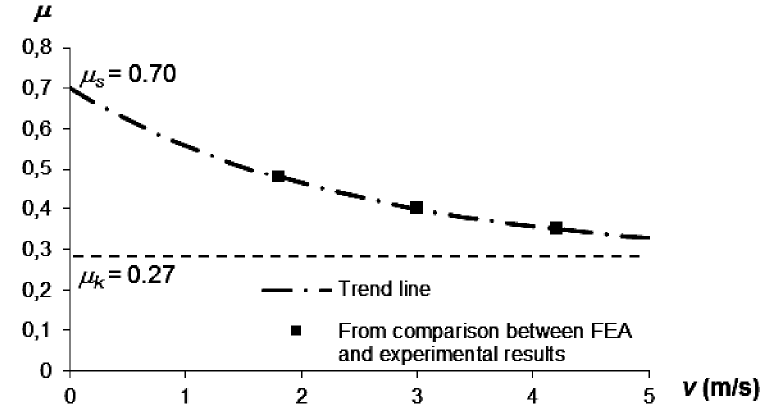


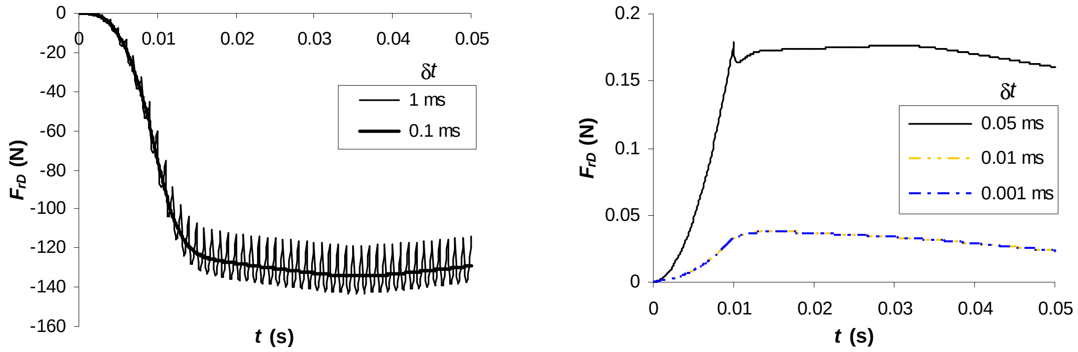
Fig. 3 Friction coefficient curve [7]

4 RESULTS

The effects of the Integration Time Step (ITS), Time Step (TS), and the number of beam elements are studied. Because in the case of a bristle impacting a surface, the contact times are minute, the ITS has to be very small. The results suggest that an appropriate maximum limit for the ITS is 5 to 10 μs. With regard to the number of beam elements in the bristle, the results indicate that 12 beam elements is an appropriate number.

Regarding the TS, δt, an appropriate value depends critically on the type of load case used. In the DispLC, the top node of the bristle follows a circular path. However, this circumference is approximated by a polygon with many sides. Due to this approximation, the velocity of the top nodes undergoes abrupt changes of direction at the intersections of the sides of the polygon. Consequently, the accelerations at those points are, in theory, infinite. Then, very high accelerations, as well as forces and moments, may be produced.

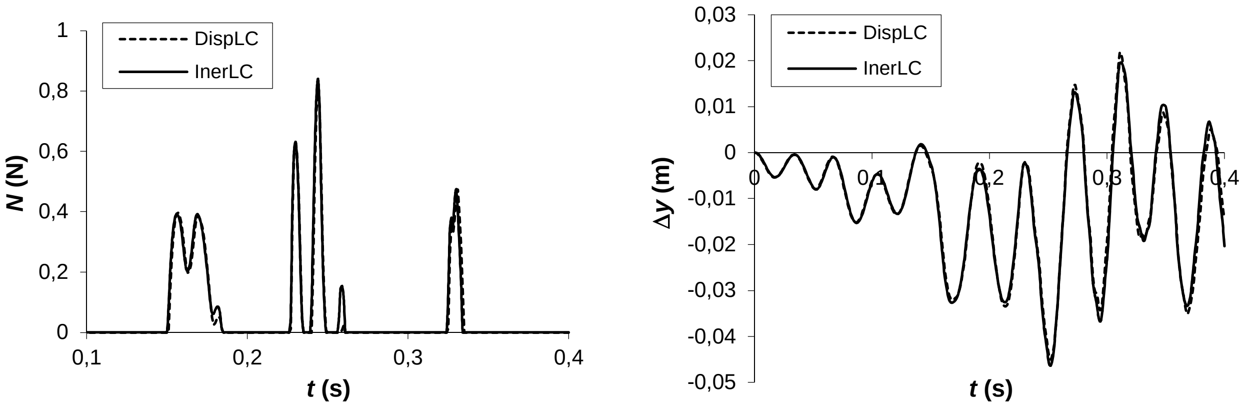
Analyses with various TS values, which affect the size of the sides of the polygon, are performed. The data for these analyses are: brush angle of attack (angle between the mounting board normal and the normal to the road surface), β = 0; the speed function is the VAP function with ω_m = 100 rpm, ω_a = 5 rpm, f = 9 Hz, and b = 0.08; mass proportional damping coefficient, α_D = 0.1 s^{-1} and stiffness proportional damping coefficient, β_D = 21 ms. The analyses reveal that the approximation of the circular path tends to produce errors relatively small in the Degree of Freedom (DOF) results, but it may produce huge errors in the forces and moments, particularly the damping components. Fig. 4 presents an example that suggests that the damping forces should be positive and less than 0.05 N. However, when δt = 1 ms, damping forces of the order of -140 N are generated. The static and inertia components of the forces and moments are also affected by the approximation of the circular path; nevertheless, their values are much smaller than the damping components. In general, the results suggest that convergence is achieved when $\delta t \lessapprox$ 0.01 ms. The small value required for δt is a reason for preferring the InerLC to the DispLC, because this would require very large computing times. It is noted that for the InerLC, convergence is practically achieved at least when $\delta t \lessapprox$ 1 ms.



(a) δ*t* = 1 and 0.1 ms (b) δ*t* = 0.05, 0.01, and 0.001 ms

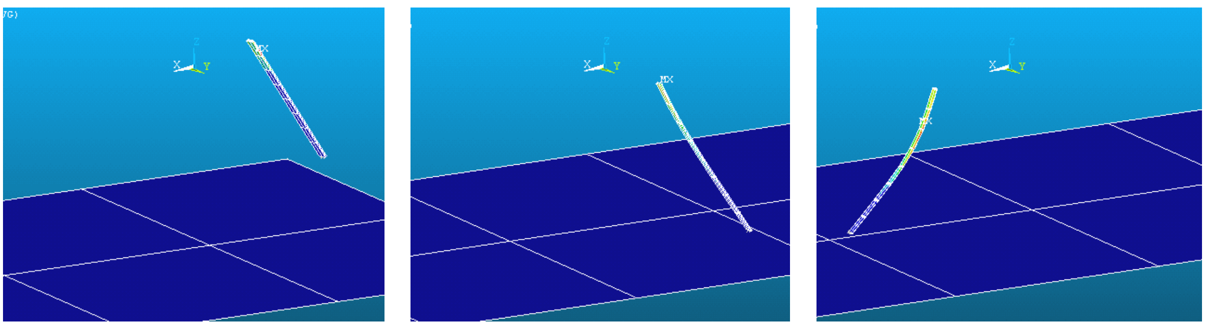
Fig. 4 Damping force at the clamped end in the brush radial direction vs. time for a number of time steps

In order to validate the two load cases, a comparison of results from both of them is carried out. The data for these analyses are: μ_s = μ_k = 0.5, brush angle of attack, β = 10°, brush penetration (i.e., vertical distance between the road surface and the tip of the bristle that withstands the greatest deflection if it could penetrate the road without deflection), Δ = 0.04 mm, brush translational speed (sweeper speed), v = 1.5 m/s. The oscillatory function is the sinusoidal function with ω_m = 150 rpm, ω_a = 4 rpm, and f = 5 Hz. No damping was considered in this analysis. Examples of the results of both models are shown in Fig. 5 to 7. It is noted that the curve for the DispLC in Fig. 5(b) is an equivalent curve, so that it can be compared with the InerLC curve. The small differences that are exhibited in Fig. 5 may be partly due to the different TS used (δ*t* = 1 ms in the InerLC and δ*t* = 0.01 ms in the DispLC) and the differences in the way in which high frequency vibrations are modelled in both cases. The DispLC tends to be very sensitive to δ*t*, and high accelerations tend to be developed due to the abrupt changes in the velocity of the top node. The InerLC tends to produce smoother values of accelerations and forces.



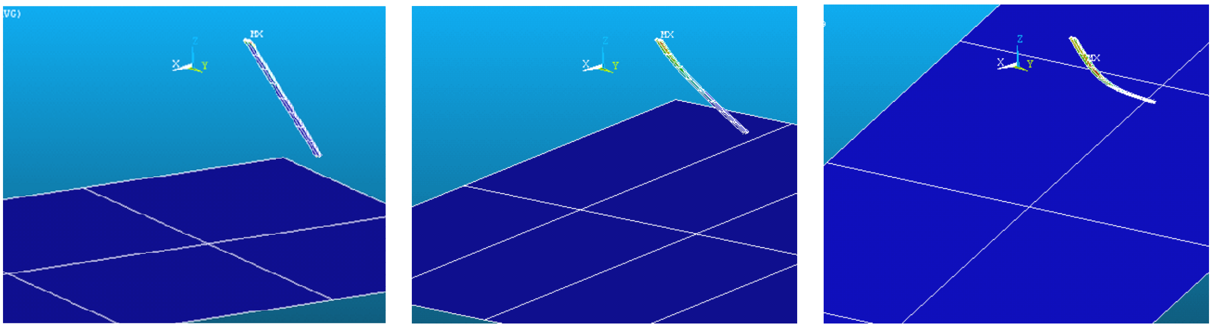
(a) Normal tip-road contact force vs. time (b) Tip displacement in the radial direction vs. time

Fig. 5 Comparison between inertia and displacement load cases



(a) *t* = 0 s (b) *t* = 0.125 s (c) *t* = 0.25 s

Fig. 6 Application of the displacement-load-case model



(a) t = 0 s (b) t = 0.125 s (c) t = 0.25 s

Fig. 7 Application of the inertia-load-case model

5 CONCLUSIONS

In this paper, two finite element models of a bristle of an oscillatory gutter brush were presented and compared. In the first model (DispLC), displacements and rotations were applied to the clamped end of the bristle, so that it rotates about the brush axis following a circular path. However, this path was approximated by a certain number of straight lines. In the second model (InerLC), the clamped end is fixed, and inertia loads were applied. Sensitivity analyses, validation, and comparison of the models were carried out. The results indicate that both models are valid and may provide accurate results. However, with regard to forces and moments, the accuracy of the model that applies displacements and rotations critically depends on the number of straight lines that approximate the circular trajectory. If the number of lines is not sufficiently large, the accuracy is very low, mainly due to the damping forces. Suitable values for the time step and integration time step were determined so that the DispLC model produces reliable results. When these values are used, both models provide practically the same results. It is concluded that applying inertia loads may be more suitable for modelling and oscillatory gutter brush, because much less computational resources are needed.

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