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Side-force coefficients on aircraft tyres in yawed and unbraked motion on dry and wet pavements



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SIDE-FORCE COEFFICIENTS ON AIRCRAFT TYRES IN YAWED AND UNBRAKED MOTION ON DRY AND WET PAVEMENTS

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SIDE-FORCE COEFFICIENTS ON AIRCRAFT TYRES IN YAWED AND UNBRAKED MOTION ON DRY AND WET PAVEMENTS

1. NOTATION, DIMENSIONS AND DEFINITIONS

1.1 Notation and Dimensions

		Dimensions
D	inflated diameter of tyre	L
d	water depth	L
d_E	effective size of aggregate in surface	L
d_{TEX}	depth of surface macro-texture	L
F_0, F_2	functions (see Equation (3.5) and (3.6), respectively)	–
$(G_{ROLL})_{YAW}$	decelerating force on rolling tyre in yaw direction	ML T ⁻²
G_{TREAD}	effective shear modulus of tread material	ML ⁻¹ T ⁻²
N	speed number	–
p_{ABS}	inflation pressure in absolute measure	ML ⁻¹ T ⁻²
q	kinetic pressure	ML ⁻¹ T ⁻²
q_v	pressure in Zone 2 (tyre footprint on wet surface)	ML ⁻¹ T ⁻²
V	ground speed	LT ⁻¹
V_{ROLL}	component of velocity parallel to plane of wheel	LT ⁻¹
V_{YAW}	component of velocity normal to plane of wheel	LT ⁻¹
w	inflated width of tyre	L
X	function (see Equation (3.6))	–
Z	vertical load on tyre	ML T ⁻¹
η_4	function (see Equation (3.5))	–
η_{40}, η_{50}	constants in model	–
κ	constant of proportionality between hoop stress and inflation pressure	–
Λ	loading parameter	–
λ	phase angle between stress and strain in tyre compound	radian
μ_{REF}	reference coefficient of sliding friction	–
μ_{ROLL}	coefficient of resistance parallel to plane of wheel	–

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μ_{YAW}	coefficient of resistance normal to plane of wheel	—
$(\mu_{YAW})_{DRY}$	coefficient of resistance normal to plane of wheel on dry runway	—
$(\mu_{YAW})_{REF}$	reference coefficient of skidding friction normal to plane of wheel on dry runway	—
$(\mu_{YAW})_{WET}$	coefficient of resistance normal to plane of wheel on wet runway	—
ρ_{TREAD}	density of tread material	ML ⁻³
$\sigma[\]$	standard deviation of quantity in []	—
$1/\tau$	drainage parameter	—
ϕ_E	effective porosity of surface	—
ψ	yaw angle	—

1.2 Definitions

<i>Coefficients of force</i>	are defined as the ratio of (horizontal) force and the normal (to the runway) force so that consistency with customary practice is maintained.
<i>Drainage parameter</i>	is the ratio of depth of free-standing water on, and the total depth of water on and in, the surface.
<i>Footprint</i>	is the jargon term for the area of contact between tyre and runway surface.
μ_{REF}	is the limiting coefficient of resistance force sustained at the interface between tyre and runway. It is proportional to the maximum shear stress that can be sustained by molecular adhesion at that interface.

2. INTRODUCTION

The model for the performance of a single aircraft tyre rolling or braking on dry or precipitate contaminated runways, detailed in Reference 1, presents a wide range of data for tyres in rectilinear motion. The model is empirical but is based on an interpretation of the physical properties of visco-elastic materials. As such, the methods are simple, straightforward, and rely only on the nominal dimensions, vertical loading and inflation pressure of the tyre. Speed and the condition of the runway surface are also taken into account.

Although it is of fundamental importance to consider all aspects of rectilinear motion of aircraft and ground-vehicle tyres, turning forces need also to be allowed for so as to enable the calculation of minimum manoeuvre speeds on the ground, steering capabilities and an understanding of the operation of such Continuous Friction Measuring Equipment as the Mu-Meter and the SCRIM.

The way in which yawing force is accounted for in currently published ESDU documentation (Reference 2) is not compatible with the approach used in Reference 1. The data on which Reference 2 rests are collected in Reference 3. However in common with much of the experimental data collected over the years, many important details are not included in Reference 3. So those *original* references that *do* contain relevant information have been revisited to further the process of formulating the model which is described in this Item.

3. MODELLING

3.1 General

It is demonstrated in Reference 1 that, in order to calculate the motion of a *braked* wheel, it is necessary to know values for variables that are associated with the runway and its condition. Also, quantities that are part of customary ground performance calculations are needed together with an indicator of braking system performance and are as follows:

- speed,
 - depth of water or slush,
 - density of water or slush,
 - tyre inflation pressure (in absolute measure),
 - vertical loading,
 - tyre width,
 - tyre diameter,
 - depth of runway macro-texture
- and
- slip ratio.

Data from tests with *freely-rolling yawed* wheels for a range of Type VII (bias ply) aircraft tyres and one Type VIII (radial-ply) aircraft tyre on concrete runways are considered in this Item. Slip ratio is therefore not required as the braking case is not taken into account. Conditions covered in the testing are given in Table 3.1.

TABLE 3.1 Modelled and validated test conditions

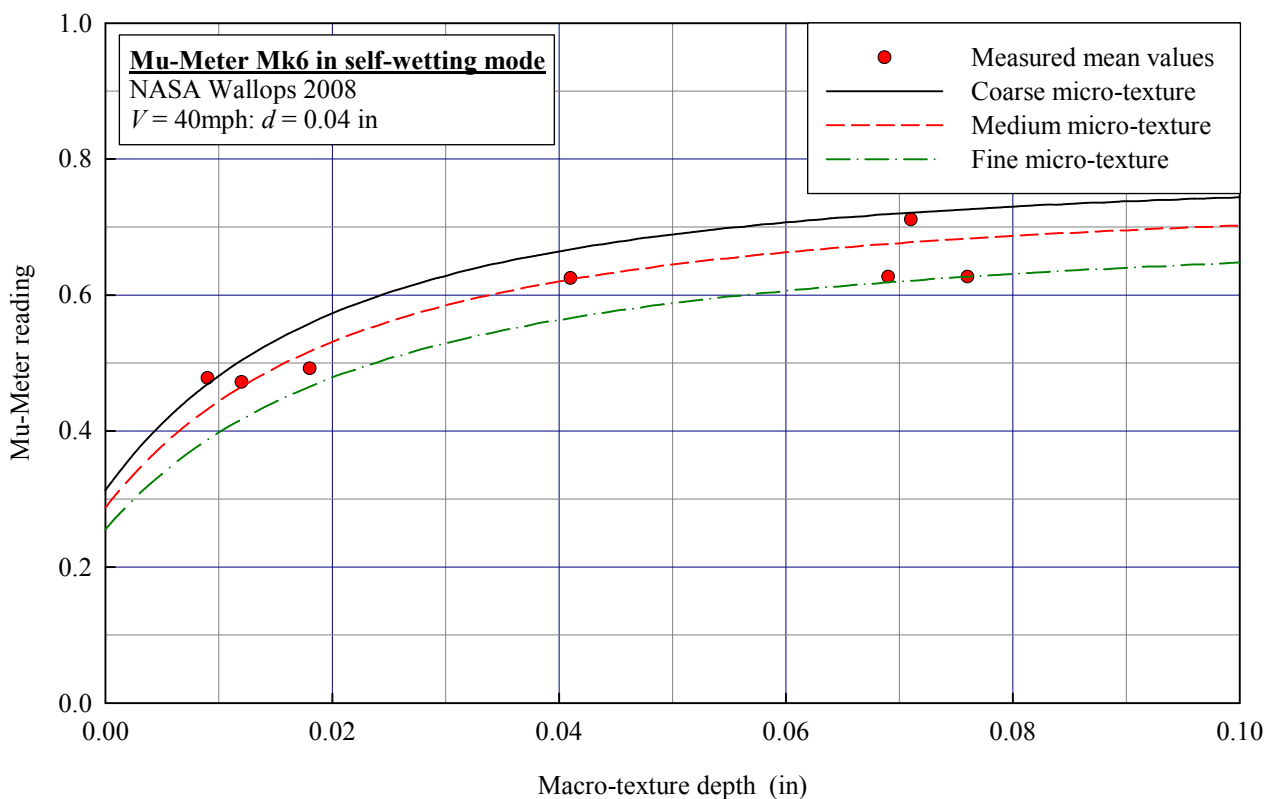
<i>Reference</i>	<i>Yaw</i> (degree)	<i>Speed</i> (knot)	<i>Inflation Pressure</i> (psig)	<i>Load</i> (lbf)	<i>Width</i> (in)	<i>Diameter</i> (in)	<i>w/D</i>	<i>Texture Depth</i> (in)	<i>Water Depth</i> (in)
6	1 to 12	40 to 100	300	5000 30000	8.8	32	0.275	0.006	Dry
7	3 to 9	50 to 100	215	2000 8000	5.5	18	0.306	0.006	Dry
7	3 to 9	50 to 100	170	16000 48000	17	49	0.347	0.006	Dry
8	8 to 24	18	107	4000	5.5	22	0.25	0.006	Dry
10	5 to 30	5 to 100	145	3300 nominal	5.5	18	0.306	0.0035 to 0.03	Damp Flooded
11	5 to 20	5 to 100	155	25000	14	40	0.35	0.003	Damp Flooded
12	4 to 12	10 to 100	165	3200	5.5	18	0.306	0.004 to 0.01	Damp Flooded
13	7.5	40 (mph)	10	171	4	16	0.25	0.009 to 0.072	0.04 (Self-wet)
Summary	Up to 30	Up to 100	Up to 300	Up to 48000	4 to 17	16 to 50	0.25 to 0.35	Up to 0.072	Up to 0.33

The modelling is developed in two phases. First, data from *dry* surfaces are considered. A reference value of coefficient of resistance normal to plane of the wheel, $(\mu_{YAW})_{REF}$, is defined. This represents the coefficient of decelerating force in a full skid at a speed determined by the component of ground velocity normal to the plane of the rolling wheel, *i.e.* $V \sin[\psi]$. This reference value is fundamental to the whole modelling process. In the dry case it is modified by a function F_0 , that depends on yaw angle, ψ , loading parameter, Λ , and the phase angle, λ , between stress and strain in the footprint.

It is important to bear in mind that a thin layer of low-strength material exists between the bulk of the tread material and the ground. It is not clear whether this layer owes its existence to the effects of heating, strain, or a combination of each of these. The study in Reference 9 is plausible but not conclusive. A correlation is presented that suggests that the effect on phase angle is directly or indirectly due to ground temperature.

In the second phase of model development, yawed motion on wetted pavements is considered. Now, the Mu-Meter registers a quantity proportional to side-force coefficient as shown in Reference 4.

It is abundantly clear in Sketch 3.1 that *macro*-texture depth in itself is insufficient to account for the variation of side-force on the variety of runway-style surfaces sited at NASA Wallops. It is emphasised that, as shown in Reference 5, the uncertainty associated with the mean values shown in Sketch 3.1 is better than ± 0.02 at the 95% level of statistical significance. It is therefore speculated that the *sharpness* of the *micro*-texture is an important variable in any modelling of side-forces. Because there exists no attested descriptor for the sharpness of micro-texture, modelling of side-forces in the wet has to account for the effects of changes in micro-texture more-or-less arbitrarily by means of a statistical analysis.



Sketch 3.1 Effect of macro-texture depth on Mu-Meter reading