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THE DYNAMIC RESPONSE OF AIRCRAFT WHEEL

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Abstract

The author of the lecture has collected and developed a method for analyzing the characteristics of parametes affecting aircraft tyre control forces, prediction of aircraft braking friction on runways, dynamics tyre-soil contact surface interaction model for aircraft ground operation and the dynamic response of an aircraft wheel to variation in runway friction.

Keywords: aircraft, dynamic response, braking friction, tyre model, surface.

1. Introduction

The author of the lecture has collected and developed a method for analyzing the characteristics of: parameters affecting aircraft tyre control forces, prediction of aircraft braking friction on runways, dynamic tyre–soil contact surface interaction model for aircraft ground operation and the dynamic response of an aircraft wheel to variations in runway friction.

2. Parameters Affecting Aircraft Tyre Control Forces

The movement of an aircraft is primarily the result of frictional force between the tyre, and the ground surface. As a result of the bad condition or the snowy, icy surface of the runway, or the transversal inclination of highways during the rolling of the tyres the probability of their transversal motion (crawling) is increased.

About the F_z force, resulting from the sideways sliding, we can get answers from:

- the F_n load on one wheel
- the lateral sliding angle β [1], [3]. (*Fig. 1*)

This relationship can be further modified by the fact that we can alter the tyre's rigidness by reducing the tyre pressure. This is permitted to increase off-road capability. Similarly, the quality of the runway and the tyre-compound used is also having effect on the above described problem [4].

The behaviour of the tyre under the effect of the moment of braking is determined by the rigidness and the frictional parameters of the tyre. We can see (on *Fig. 2*) the rolling of a wheel at the speed of V_x under the load of F_n.

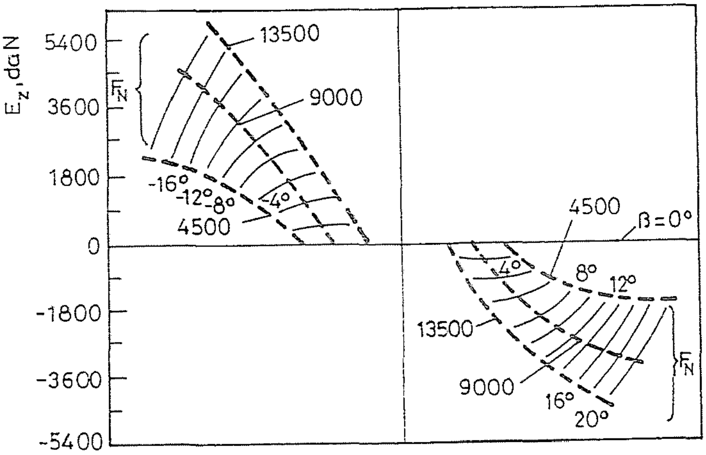

Fig. 1. F_z, F_n and β relationship

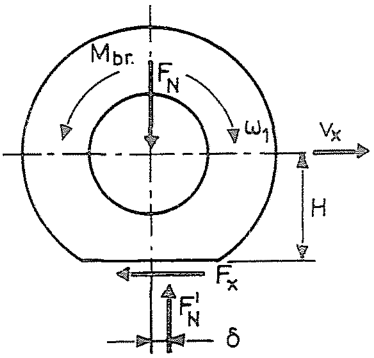

Fig. 2. The wheel model

Form this, the relative turn-over can be calculated, which is:

$$S = \frac{\omega_0 - \omega_1}{\omega_0}. \tag{1}$$

The $S = 0$ means the free-rolling of the wheel while $S = 1$ means that the wheel is blocked [1].

Under braking, the speed of motion (*Fig. 3*) and the amount of dirt on the runway (*Fig. 4*) are the major influencing factors on the friction of the wheel. On *Fig. 3* at the point $S = 0$ the C_s rigidness – characteristic of every tyre – can be marked. On *Fig. 5* the effect of the thickness of the water layer on a wet runway is shown [3].

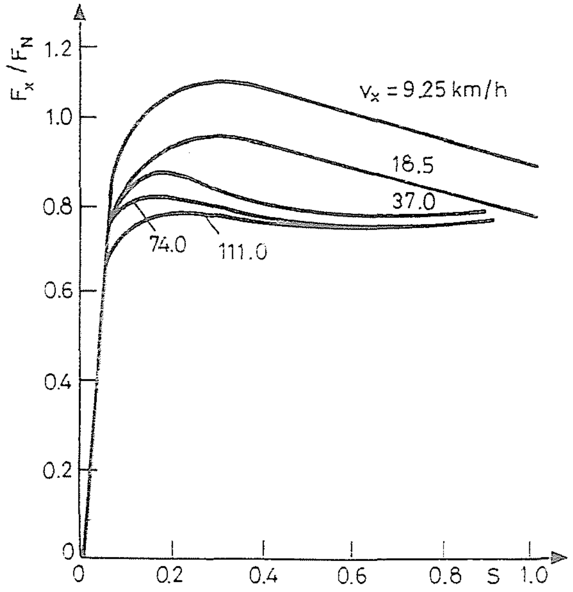

Fig. 3. Influence of the speed on the friction force

The thing of interest about the diagram is that the points of stable and unstable operation can be marked (*Fig. 6*) [4].

In practice, the modern anti-blocking systems (ABS) adjust the maximum coefficient of friction between the tyre and the runway. On wet, dirty or improperly prepared runways, this marginal relationship suddenly decreases which results in the loss of control in the steering of the aircraft along the runway or in the loss of stability during landing. Hence, this reduces the usability of maneuver airfields and highways. This is shown on *Fig. 7* [4].

This gives rise to the problem that for the operators of the aircraft, it is important to know better the most optimal relationship achievable between the longitudinal and transverse forces without the worsening of the parameters of the takeoff and landing.

3. Prediction of Aircraft Braking Friction on Runways

During the researches made by the US Air Force, NASA, and the FAA between 1968 and 1980, it was shown that this problem cannot easily be

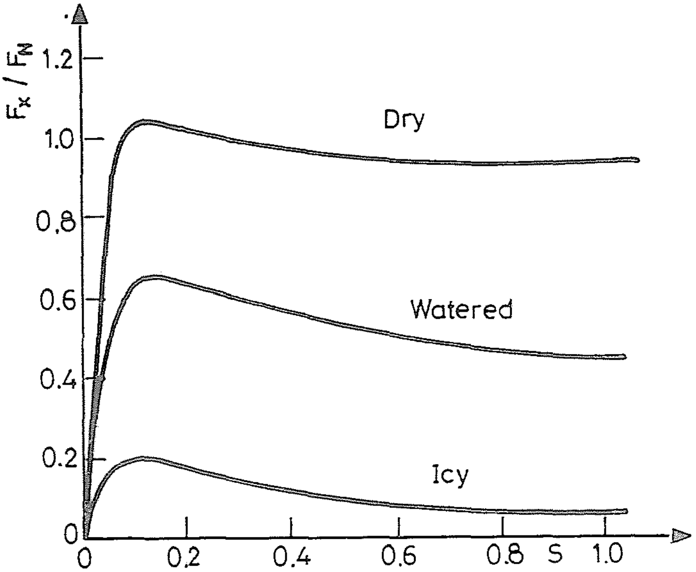

Fig. 4. Influence of the runway state on the friction force

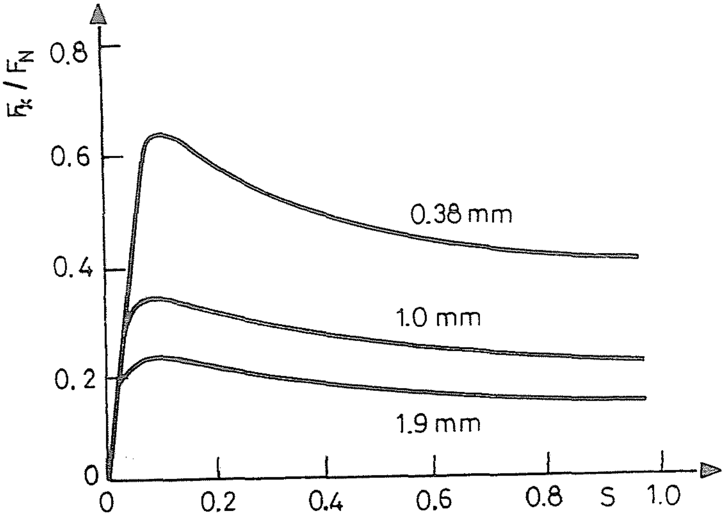

Fig. 5. Influence of the water layer thickness on the friction force

modelled. From their experiments they have reduced that there are 47 such characteristic parameters of the tyre which need to be examined for the correct description of the rolling tyre's frictional relationship.

I think, in harmony with part I, the following 19 basic parameters should be considered:

parameters of the tyre:

1 load F_n, F_z, F_x
2 inside pressure $P_{t,0}, P_{t,1}$
3 construction of the tyre (e.g. radial, diagonal, etc.)
4 texture of the abrasive layer
5 size of the wheel (D^*B, d^*b)
6 the method of the strengthening of the abrasive layer
7 the type of material used for the strengthening of the abrasive layer (natural or synthetic)
8 the amount of wear of the tyre

parameters of the liquid layer covering the runway

9 viscosity
10 density
11 thickness of the layer

parameters of the runway surface

12 microstructure
13 macrostructure
14 friction measured with a polished tyre
15 friction measured with a worn, eroded tyre
16 stability against erosion
17 temperature
18 the marginal point between rolling and blocking
19 frictional coefficient under braking

In other words, these parameters include all the parameters of grass airfields, temporary covering layers, concrete runways in bad condition and of highways together with the parameters of the aircraft tyre.

For example the sliding theory developed by the NASA is interesting because it gives explanation for the rolling of the tyre on wet surfaces but it is inaccurate about the calculation of the forces creating this relationship [2].

The experiments conducted by the NASA have confirmed the relationship between some parameters on wet runways:

- radial load
- size, structure, texture of the tyre
- depth of canals on the tyre surface
- composure of the abrasive layer
- temperature
- thickness of water layer
- structure of the top (covering) layer of the runway
- mode and position of the turning wheel

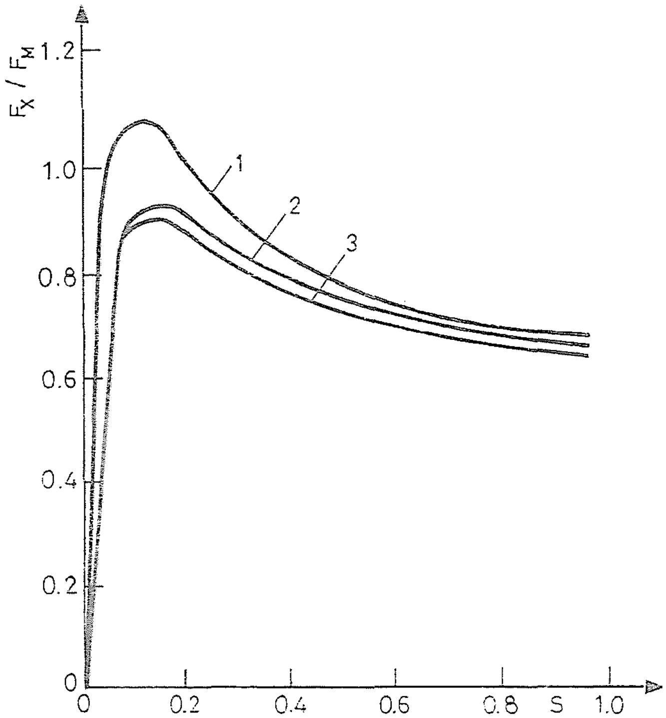

Fig. 6. Stable and unstable operation points

Fig. 8 shows the effects of the wear of the tyre of a 32*8, 8 VII wheel having longitudinal canals and an inside pressure of 1.03 MPa, having been used on a wet runway [1], [2].

Markings of the diagram are:

1. average μ
2. rolling speed
3. wear of tyre in percentages

4. Dynamic Model for the Interaction between Tyre and Soil during Aircraft Ground Operation

To ensure the operation of aircraft from grass airfields – along other considerations – it must have certain 'cross-country' capability [4].

The 'ability-to-pass' include the following most important conditions:

- the determination of the effects of the deformation of the soil
- the condition of coming into motion from standstill

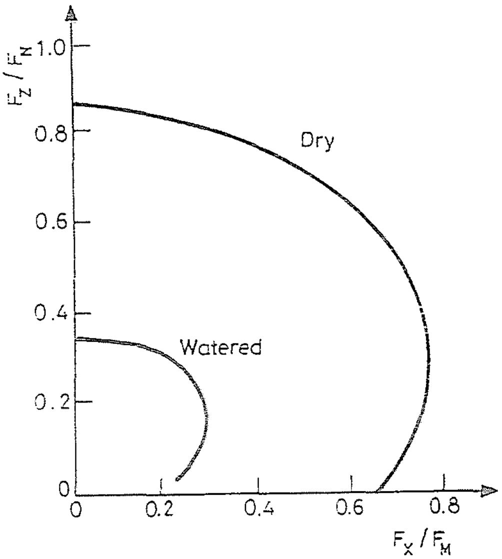

Fig. 7. F_x/F_n and F_z/F_n relationship

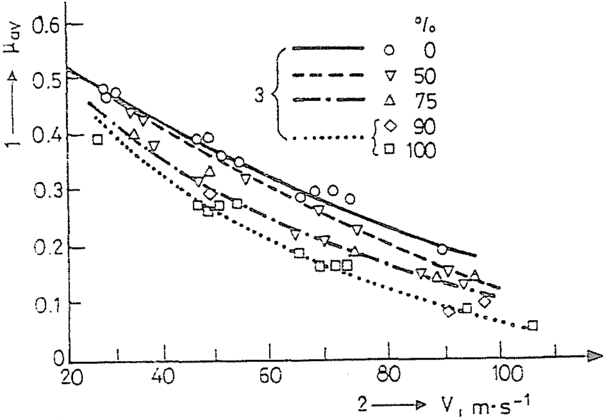

Fig. 8. Influence of the tyre wear rate on the friction coefficient

- the determination of the allowable imprint of the tyre
- the ensuring of the necessary length of runway for a takeoff-run
- the landing forces of the undercarriage

I suppose that the 'ability-to-pass' can be increased by decreasing the tyre pressure from $P_{t,0}$ to a smaller value of $P_{t,l}$ although this alters the tyre's rigidness as well.

The coefficient of the resistance of the soil deformation can be determined with the newly altered rigidness:

$$\frac{f_1 = q_{ff}}{c \cdot \xi \cdot \alpha_{\mathrm{soil}} \cdot k_1}\;, \tag{2}$$

where:

q_{ff} : the specific load on the main wheels;
c : the ratio of the depressed surfaces (*Fig. 9*);
ξ : the correctional factor due to the change in the tyre's rigidness, (*Fig. 10*);
k_1 : a factor which in the case of several wheels being on the main-wheel strut takes into consideration the effect of the second wheel on the deformation of the soil.

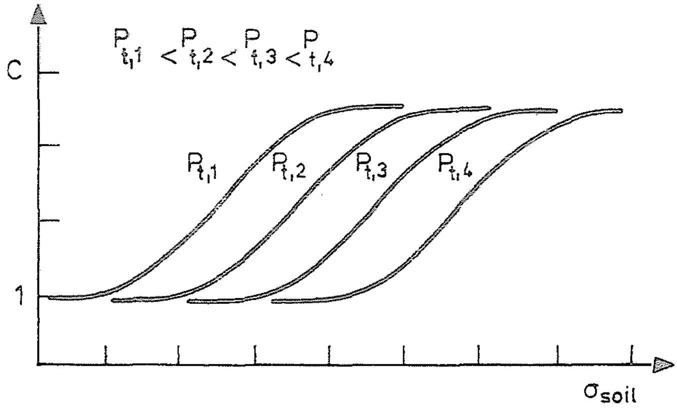

Fig. 9. The depressed surface ratio

In such cases, the necessary thrust of the aircraft to start from standstill is:

$$\mu_p = \frac{F_p}{G} \geq k_{\mathrm{soil}} \cdot f_1\;, \tag{3}$$

where

F_p : the necessary thrust of the powerplant, N;
μ_p : the thrust-to-weight ratio
G : weight of the aircraft
k_{soil} : correcting factor, which takes into consideration 5 minutes of standing before starting on different soils of different state.

Thanks to the large thrust-to-weight ratio of modern aircraft it is not this previous data which restricts the operation of aircraft from grass airfields. The allowable maximum sinking of the tyre is:

$$h_{\mathrm{allowable}} = 0.07 \cdot B \cdot D^{0.25}\;, \tag{4}$$

where B, D are the geometrical sizes of the wheel.

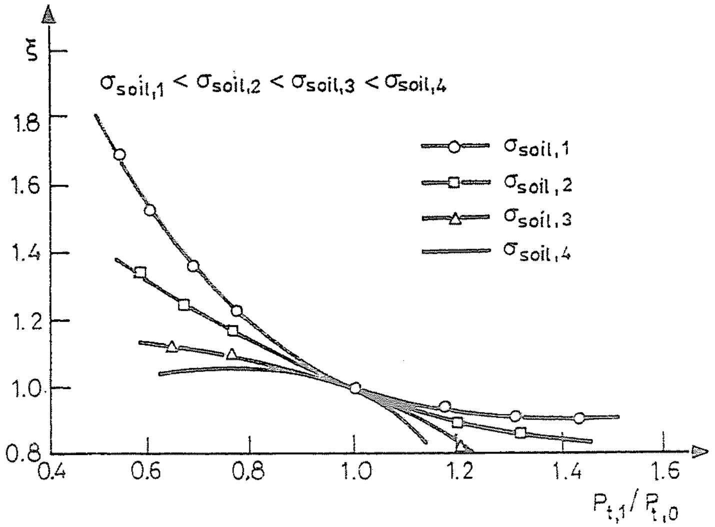

Fig. 10. The correctional factor-tyre's rigidness ratio relationship

Regarding the fourth criterion on the usability, it must be guaranteed that the takeoff and landing run of the aircraft must be smaller than the available length of grass runway together with the final security zone. These criteria may also restrict the utilization of grass airfields.

Amongst the conditions of operation, apart from the takeoff weight, the inside tyre pressure is of great importance according to BREWER's theorem. The permitted change in tyre pressure during takeoff and landing will be the following [1] [4]

$$p_{t,1} = (p_{t,0-cat}) \cdot \frac{F_{n_{t,0}}}{F_{n_{t,0-cat}}} ; \quad (5)$$

$$p_{t,2} = (p_{t,0-cat}) \cdot \frac{F_{n_{land}}}{F_{n_{land-cat}}} . \quad (6)$$

The critical takeoff and landing speeds are:

$$v_{to.cr} = \left[v_{to.max-cat} + 20 \cdot (p_{t,1} - p_{t,0})\right\} \cdot \frac{F_{n_{to-cat}}}{F_{n_{to}}} \cdot \frac{p_{t,1}}{p_{t,0}} ; \quad (7)$$

$$v_{land_{cr}} = \left[v_{land_{max-cat}} + 20 \cdot (p_{t,2} - p_{t,0})\right\} \cdot \frac{F_{n_{land-cat}}}{F_{n_{land}}} \cdot \frac{p_{t,2}}{p_{t,0}} , \quad (8)$$

where:

$p_{t,1}$: the minimum permitted pressure during takeoff, MPa;

$p_{t,2}$: the minimum permitted pressure during landing, MPa;

$F_{n.to}, F_{n.land}$: the actual load on the wheel during takeoff and landing, N;

$F_{n.to.cat}, F_{n.land.cat}$: the maximum load on the wheel according to catalogue, N;

$v_{(to.max.cat.)}, v_{(land.max.cat)}$: the manufacturer's restriction on speed after the installation of a type, according to catalogue, m/s.

The maximum weight-bearing capacity related to the above mentioned depending on the sub-layers of soil can be determined with the aid of the – locally well-known – Dorni method.

Obviously there are more modern methods of determining the 'ability-to-pass', but considering the tools at my disposal, I am able to calculate with this one.

In this part, the problem is caused by the fact that by reduction of the tyre pressure, its rate of exhaustion increases, its lifetime decreases [4].

5. The Dynamic Response of an Aircraft Wheel to the Variation in Runway Friction

At the Department of Aerospace at the Bristol University, they have been examining the problem of the ground motion of aircraft since 1970. For this research they have built a linear dynamometric device which was the first capable of examining the friction of an aircraft wheel when it was rolling on a softer surface than that of the tyre at a certain inside pressure. Later on, they have improved on this device by making it capable of examining the dynamic reactions of a braked aircraft on different solid-surfaced runways [5].

In doct. univers dissertation I have collected some temporary types of surfacing materials, which are used for the covering of maneuver airfields. Because the researches made at Bristol also include such materials, hence the dynamic properties of the wheel can be well-examined for the research of the earlier mentioned problem.

The experiment was done on the following types of surfaces:

1. WA : wet aluminium sheet
2. LWA : slightly wet aluminium sheet
3. DA : dry aluminium sheet
4. DS : dry aluminium sheet covered with sand grains

The appropriate sign for the type of surface used in the experiment can be found on the time oscillograph. During the movement of the chassis across the different surfaces, the dynamic reactions of the wheel changes according to the frictional relationship and its value can be measured. Similarly, a detector is used on the surfaces which records the time when the wheel crosses the boundaries of the different sectors of surfaces

The results of a typical run can be seen on *Fig. 11* which has the marking of:

(1) markings of the boundaries of different sectors
(2) serial number of the type of surface
(3) time in ms

At the beginning, the wheel with a given vertical load and with a certain braking moment is crossing the DA surface which has a small coefficient of friction, which resulted in the blocking of the wheel (the relative turn-over was 1).

After this came along the DS sheet with a large coefficient of friction. The increasing frictional force starts to rotate the wheel, thus the relative turn-over is 0. The process is determined by the frictional coefficient μ, F_s frictional force movement, ω_w angular speed of the wheel, and the S_ω relative turn-over S_w [5].

The experiments call our attention to two phenomena, which are based on the flexibility of the tyre. The first one is apparent when the primarily blocked wheel works along the surface of a large coefficient of friction, the increase in μ is halted while the wheel reacts and starts to slow down. The second phenomenon can be determined from expriments. After the intensive turn-over, on the DS surface, quickly dampening small amplitude angular velocity oscillations of around 62 Hz can be seen. This phenomenon results from the fact that there is a relative motion between the wheel-base and the surface of contact.

Experiment can be shown with mathematical methods as well. The two-free-axis model is shown on *Fig. 12*.

The equations of motion are:

$$
\begin{aligned}
m \cdot a &= -F_s \,, && (9)\\
I_1 \cdot \varepsilon_W &= (\omega_t - \omega_W) \cdot K_t + (\alpha_t - \alpha_W) \cdot C_t - M_{br} \,, && (10)\\
I_2 \cdot \varepsilon_t &= H \cdot F_s - (\omega_t - \omega_W) \cdot K_t - (\alpha_t - \alpha_W) \cdot C_t - \\
&\quad F_n \cdot \left(\mu_g \cdot H - \frac{F_s}{C_s}\right) \,, && (11)\\
F_s &= \mu \cdot F_n \,, && (12)\\
S_t &= 1 - r_{e,0} \cdot \frac{\alpha_t}{x} \,, && (13)\\
S_w &= 1 - r_{e,0} \cdot \frac{\alpha_W}{x} \,, && (14)\\
r_{e,0} &= r_0 - \frac{\delta_0}{3} \,, && (15)
\end{aligned}
$$

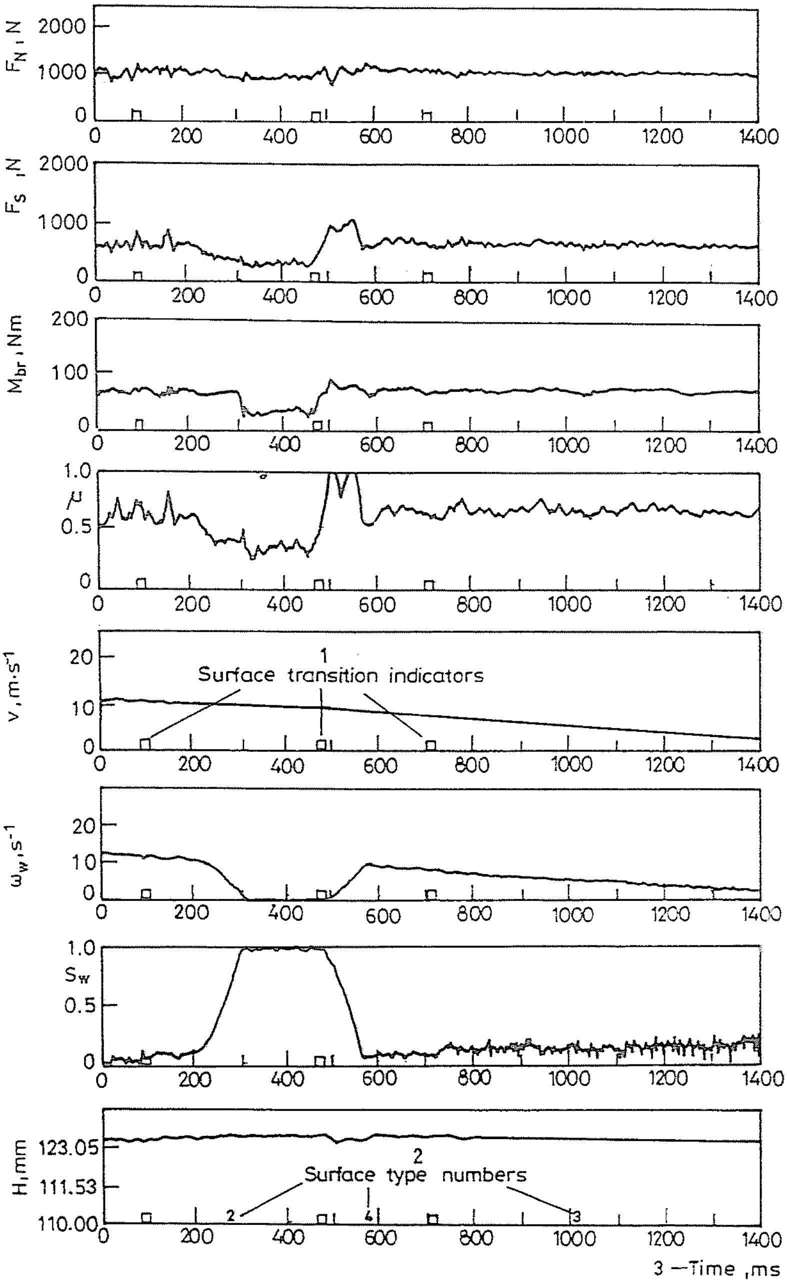

Fig. 11. Typical run's results

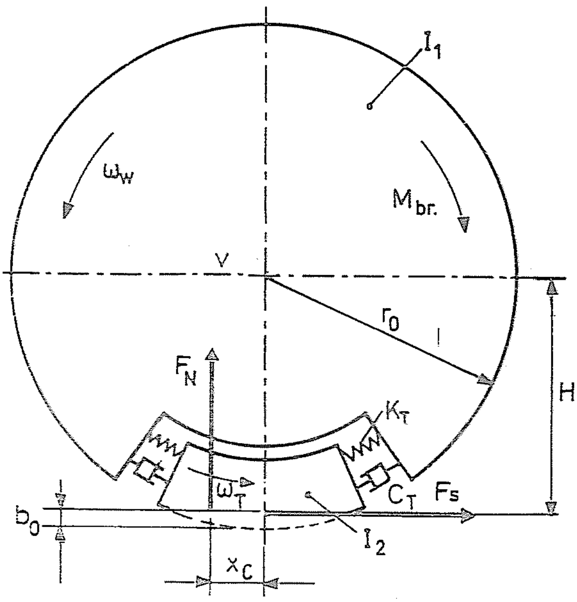

Fig. 12. The two-free-axis model

where K_t, C_t and I_z were determined through experiments. The coefficient of friction μ was determined through experiments as well.

When the relative turn-over is positive, that is

$$\mu = \mu(S_t, P_{t,0}, x, M_{brake}, \text{type of surface}); \quad S_t > 0 \tag{16}$$

when $S_t = 0$, then:

$$\alpha_t = \frac{x}{r_{e,0}}; \quad \omega_t = \frac{v}{r_{e,0}}; \quad \varepsilon_t = \frac{a}{r_{e,0}}. \tag{17}$$

We can diminish the variable ω_t and its derivatives from the equation. Therefore with the combination of the equations we get the following:

$$m = \frac{\left(\frac{x}{r_{e,0}} - a_w\right) \cdot K_t + \left(\frac{v}{r_{e,0}} - w_w\right) \cdot C_t + m_g \cdot F_n \cdot H}{F_n \cdot \left(H + \frac{I_2}{m \cdot r_{e,0}} + \frac{F_n}{K_x}\right)}; \quad S_t = 0. \tag{18}$$

The calculations with any combination of initial conditions, can be done with the use of the appropriate surface. The system of differential equations can be integrated with the aid of the Runge-Kutta method. The results acquired from the mathematical model of two-free-axis are similar to those which were obtained when the flexibility of the abrasive layer was not taken into account.

6. Conclusions

The adoption of the flexibility in the model resulted in the appearance of the angular parameters of the oscillations of the wheel during its full turn-over. The oscillation frequency of the mathematical model was the same as that of the experimental device, which proves the existence of motion between the wheel-base and the tyre and at the same time presumes the flexibility of the tyre.

The effect of the above mentioned flexibility of the tyre on the dynamics of the rolling of the braked wheel may decrease the efficiency of the ABS and braking system of the aircraft. The dynamical influences related to tyre flexibility can be made perceptible during the design of such systems only with the aid of the two-free-axis model [4], [5].

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