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Summary

Hydroplaning of aircraft tires is often a contributing factor in take-off and landing overrun and veeroff accidents. Therefore hydroplaning of aircraft tires has been studied for many years. The majority of the current knowledge on hydroplaning was obtained in the 60's by mainly NASA studies. Since then new tire types like radial tires were introduced for civil aircraft. This paper discusses the hydroplaning characteristics of these modern tires. Simple theoretical models are presented to analyse the hydroplaning characteristics. It is concluded from this analysis that modern tires have lower hydroplaning speeds than previously assumed. To further confirm the results found in this paper, it is recommended that systematic tests should be conducted on the static mechanical characteristics of modern aircraft tires in combination with hydroplaning tests.



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1 Introduction

Hydroplaning of aircraft tires is often a contributing factor in overrun and veeroff accidents. Therefore hydroplaning of aircraft tires has been studied for many years. The majority of the current knowledge on hydroplaning was obtained in the 60's mainly by NASA studies (see e.g. Ref. 1). Since then new tire types like radial tires were introduced for civil aircraft. This paper will discuss the hydroplaning characteristics of these modern tires. Simple theoretical models in combination with empirical data will be used to analyse the hydroplaning characteristics.

2 Theory of hydroplaning

When a tire rolls along a wet surface, it is squeezing water from under the footprint. This squeezing process generates water pressures on the surface of the tire footprint. At a critical speed the tire will be completely separated from the ground surface by a film of water. This speed is called the hydroplaning speed. The water pressure build-up under the tire originates from the effects of fluid density and fluid viscosity. Two types of hydroplaning can be distinguished:

- Dynamic hydroplaning
- Viscous hydroplaning

In general both types of hydroplaning can occur at the same time. This paper will focus on dynamic hydroplaning because this is the most important one.

Dynamic hydroplaning is the result of the hydrodynamic forces developed when a tire rolls on a water covered surface. This is a direct consequence of the tire impact with the water that overcomes the fluid inertia. The magnitude of the hydrodynamic force varies with the square of the tire forward ground speed and with the density of the fluid. Dynamic hydroplaning is influenced by tire tread, water layer thickness and runway macrotexture. Macrotexture is the runway roughness formed by the large stones and grooves in the surface of the runway. When there is sufficient macro texture on the surface and / or the tire has proper tread, total dynamic hydroplaning will usually not occur. However, hydroplaning can occur when the water depth is high enough so that both tire tread and runway macro texture cannot drain the water quick enough.



The hydrodynamic dynamic lift generated under a tire rolling along a water-covered surface is given by (Ref. 1)

$$L = \frac{1}{2} \rho V^2 S C_{Lh} \quad (1)$$

with ρ density of the fluid, S the tire footprint area and C_{Lh} the hydrodynamic lift coefficient. When total dynamic hydroplaning occurs, L/S is equal to the tire bearing pressure that can be approximated by the tire inflation pressure p (Ref. 1). Hence, the total dynamic hydroplaning speed is given as

$$V_p = \sqrt{\frac{2}{C_{Lh}}} \sqrt{\frac{p}{\rho}} \quad (2)$$

For a free rolling tire C_{Lh} is about 0.7. However, for a sliding tire (e.g. a tire that has to spin-up just after touchdown) C_{Lh} is about 0.95. It appears that it is more difficult for a fluid to escape from a sliding tire than from a rolling tire. The value of 0.95 is based on ad hoc tests conducted by NASA Langley (Ref. 2). The value of 0.7 is based on a large number of tests including full-scale aircraft.

Using a hydrodynamic lift coefficient of 0.7 and the density for water, Eq. 2 simplifies to

$$V_p = 9\sqrt{p} \quad (3)$$

with p in psi and V_p in Kt. This equation is simply known as Horne's equation for dynamic hydroplaning. For many years Eq. 3 has been used to predict the hydroplaning speed of aircraft tires.

Eq. 3 is presented in most of the literature on hydroplaning. An alternative approach to analyse dynamic hydroplaning will be discussed now. Assume that a state of total hydroplaning has been reached. The tire footprint is now completely supported by a water film over a length L_f (footprint length). Consider a tread element on the surface of the tire. The time (t) which the tread element needs to penetrate the water film completely, is given by (ref 3)

$$t = \frac{L_f}{V_p} \quad (4)$$



It can be shown that t is a function of tire pressure p , fluid density ρ and footprint width W_f (See Ref. 3)

$$t \cong W_f \sqrt{\frac{\rho}{p}} \quad (5)$$

Combining Eq. 4 and 5 results in a relation for the hydroplaning speed

$$V_p = \lambda \frac{L_f}{W_f} \sqrt{\frac{p}{\rho}} \quad (6)$$

where λ is a constant, which depends on surface texture, tread of the tire and water depth. It follows directly from Eq. 6 that the longer and the more narrow the footprint is, the higher the hydroplaning speed becomes. In both Eq. 6 and Eq. 2 the influence of tire pressure and fluid density is presented in a similar way. It follows from Eq. 6 that the hydrodynamic lift coefficient (C_{Lh}) is a function of tire footprint width and length, surface texture, tread of the tire and water depth.

$$C_{Lh} = \frac{2}{\lambda^2} \left(\frac{W_f}{L_f} \right)^2 \quad (7)$$

The value of 0.7 for the lift coefficient of a rolling tire given in for instance Ref. 1 is based on experiments where the water depth was greater than the tire grooves and surface texture (flooded runways). For such conditions λ can be considered as an overall constant (Ref. 3).

Therefore, for flooded runways the lift coefficient is a function of the tire footprint aspect ratio (W_f / L_f) only. Harrin in Ref. 4 suggests a value for λ of 1 based on some limited experimental data. Similar values are found from theoretical calculations (See Ref. 3). Using this value for λ ($=1$) and typical tire footprint aspect ratio's for aircraft tires in the range of 0.58 - 0.65, C_{Lh} varies between 0.67 and 0.85. These values compare well with a theoretical value of 0.8 given by Martin in Ref. 5 and also with the experimental value determined by NASA (0.7). So for flooded runways the hydroplaning speed is determined by tire inflation pressure, fluid density and tire footprint aspect ratio.

For a tire that needs to spin-up after touchdown, the constant λ is assumed to be equal to 0.85 based on the results presented in Ref. 2. However, detailed full-scale experiments are necessary to confirm this. Note that experiments conducted by the Davidson Laboratory using an open cell



polyurethane model tire, suggest a λ of 0.8 (See Ref. 6). This value is similar to the one presented by Pinsker in reference 7.

The influence of tire footprint aspect ratio was initially not considered in the NASA hydroplaning studies. However, in 1984 Horne published a paper in which he analysed the effect of tire footprint aspect ratio (Ref. 8). Horne showed that tire footprint aspect ratio has a significant influence on the hydroplaning speed.

3 Hydroplaning speeds of modern aircraft tires

3.1 Predicted hydroplaning speeds

With help of equation 6 it is possible to analyse the hydroplaning characteristics of aircraft tires. The following three tire types were considered for this: bias-ply tire, type-H tire and a radial-belted tire. The tire footprint characteristics (footprint length and width) were calculated using empirical equations presented in Ref. 9. These empirical equations were developed using the results from static tests with the three tire types. In Figure 1 the theoretical hydroplaning speed as function of tire pressure is presented for a 40x14 tire with a vertical load of 40,000 Newton. Equation 3 is also included in Figure 1. Figure 1 clearly shows that for a given tire pressure the hydroplaning speeds of all three tire types is lower than the hydroplaning speed predicted by equation 3. The radial-belted and H-type tires have significantly lower hydroplaning speeds than the bias-ply tire. This is caused by the difference in tire footprint characteristics of these tires. Note that the approximations for the hydroplaning speeds for the three tires given in the brackets in Figure 1, should be used with caution. For different tire sizes and vertical loads these approximations will be slightly different. However the results can be used as a first approximation.

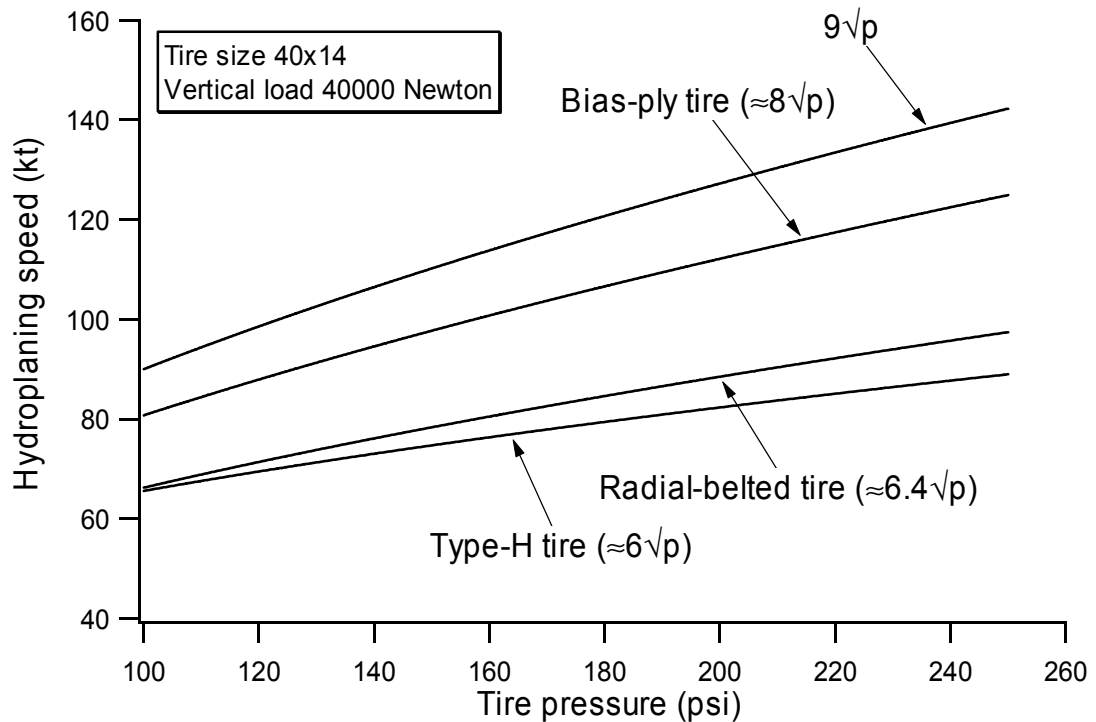


Figure 1: Theoretical hydroplaning speeds for three tire types.

3.2 Experimental hydroplaning speeds

To support the findings of section 3.1 some experimental data on hydroplaning speeds of modern aircraft tires will be presented. Results of full-scale hydroplaning tests are shown in Figure 2. From Figure 2 it can be seen that the older bias-ply tires correlate reasonable well with Horne's equation (Eq. 3). However, newer bias-ply tires, type-H tires and radial-belted tires have lower hydroplaning speeds than predicted by equation 3. Unfortunately, obtaining accurate hydroplaning speeds from full-scale aircraft tests is difficult. For instance the vertical load on the tires will be fluctuating, tire pressure can fluctuate due to heating of the brakes, fluid depth is not constant etc. This will introduce scatter in the experimental derived hydroplaning speeds shown in Figure 2. Furthermore there is no common method to derive the hydroplaning speed from experiments. All this suggests that further systematic tests on single tires should be conducted with a common definition for determining the hydroplaning speed.

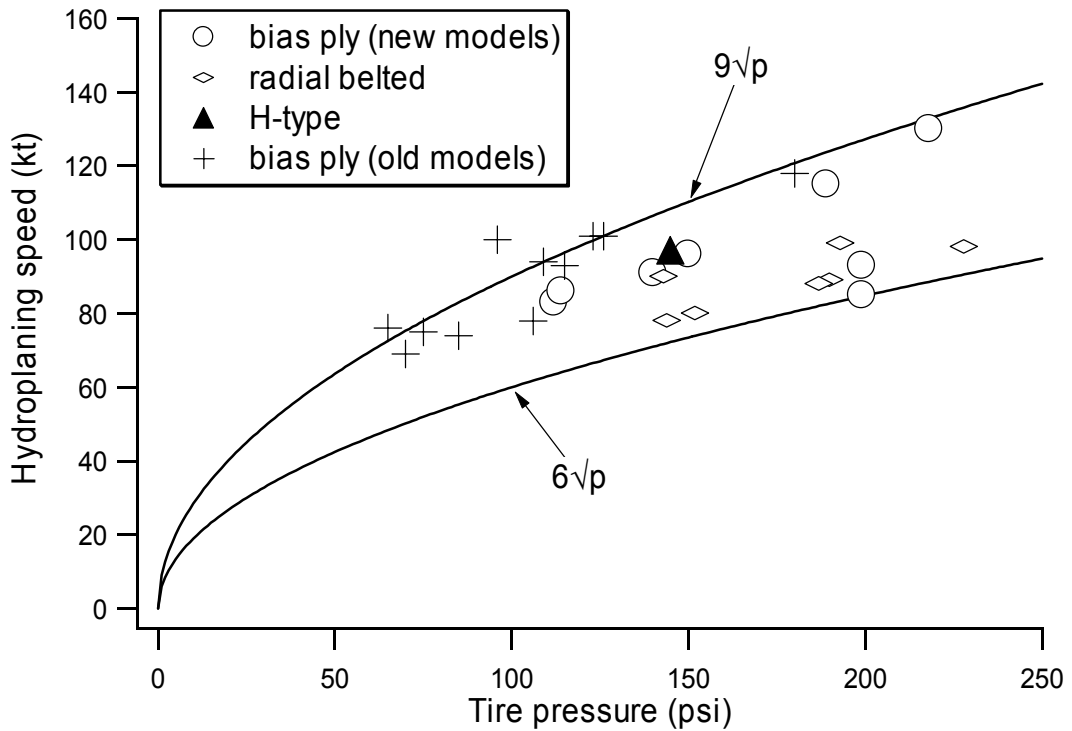


Figure 2: Experimental hydroplaning speeds as function of tire pressure for different tire types.

4 Conclusion

It is concluded from the results presented in this paper that modern aircraft tires have lower hydroplaning speeds than prediction by the well-known and commonly accepted equation developed by Horne from NASA.

5 Recommendation

To further confirm the results found in this paper, it is recommended that systematic tests should be conducted on the static mechanical characteristics of modern aircraft tires in combination with hydroplaning tests. NASA's Aircraft Landing Dynamics Facility could be considered to conduct such tests.



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