Aerospace Science and Technology 72 (2018) 49–62

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Flow physics and chine control of the water spray generated by an aircraft rigid tire rolling on contaminated runways

Kaibin Zhao, Peiqing Liu, Qiulin Qu *, Pingchang Ma, Tianxiang Hu

Beijing University of Aeronautics and Astronautics, Beijing, 100191, China

ARTICLE INFO

Article history:
Received 25 October 2016
Received in revised form 19 October 2017
Accepted 27 October 2017
Available online 31 October 2017

ABSTRACT

During the take-off and landing of aircrafts from/on water-contaminated runways, the tire-generated water spray can endanger flight safety, such as engine spray ingestion and spray impingement drag. In this paper, the flow physics and chine control of the spray generated by an aircraft rigid tire are studied by the Smoothed Particle Hydrodynamics (SPH) method. The SPH method is validated by a NASA experiment. The forming and developing progresses of the front and side sprays are described in detail. It is found that the parabolic stripe of initial ejected particles at a given time is the boundary between the spray source region and the non-disturbed region in water film, and the stripes at any time are similar. The effects of tire speed and water film depth on spray angles are evaluated. The chines can effectively control the spray angles by reducing the vertical velocity component of the ejected particles and increasing the lateral component. The arc chines are more effective in controlling the spray than the linear chines.

1. Introduction

A runway is considered to be contaminated by water, when more than 25% of the runway surface area (within the reported length and the width being used), is covered by more than 1/8 inch (3 mm) of liquid water in depth [1,2]. The take-off and landing of aircrafts from/on contaminated runways will present serious problems such as tire-generated water spray. The water spray ingested by engines as the airplane passes through water standing on runways and taxiways may cause engine surge, stall or even flame-out. In addition, the water spray impingement on any airframe component will create additional drag and increase the take-off ground-run, and even damage the airframe components. Every type commercial aircraft must pass the water spray test before operating according to the airworthiness requirements. Therefore, the researches on water spray generated by tires rolling on a water-contaminated runway are helpful to safe take-off and landing.

Aircraft tire-generated water spay is a very complex physical process, which contains several flow phenomena with different mechanism (deformation and fragmentation of water film, breakup of jet flow, deformation of droplets, droplets motion in airflow field, etc.). The tire rolling through water film develops a wave because the water is washed away from the tire track. The resulting wave contains enough energy due to the large load and high taxiing speed of tires, such that the water surface tension force can no longer keep the wave integrated and the water film starts to separate into spray. In front of the tire a wave develops, ejecting the spray in forward and upward directions. Besides the tire a side wave develops, ejecting the spray sideways and upward. The Society of Automotive Engineers (SAE) [3] defines the wave in front of the tire as Bow Wave and the wave besides the tire as Side Plume as shown in Fig. 1.

The aircraft tire performance on wet runways has been studied mainly by means of experiments long ago. The majority of the early literature concerned hydroplaning and tire/runway friction. The experimental studies on aircraft tire-generated spray on contaminated runways were few. Horne et al. [4] conducted a series of taxi tests at the NASA Langley landing-loads track with an aircraft tire rolling in both slush and water. The tests mainly concerned the tire retardation forces and neglected the water spray. Barrett [5–8] performed a series of model tests using a moving runway and water layer model test facility at Bristol University, which mainly concerned the drag and spray problems of single and twin wheels. Daugherty and Stubbs [9] conducted a series of experiments at NASA Langley Research Center to measure the flow rate and trajectory of water spray generated by an aircraft tire operating on a flooded runway. The effects of forward speed, tire load, and water depth were evaluated by measuring the amount and location of water spray captured by an array of tubes mounted behind the test tire. But in view of the difficulty of quantitative measurement by

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* Corresponding author.
E-mail address: qql@buaa.edu.cn (Q. Qu).

https://doi.org/10.1016/j.ast.2017.10.036
1270-9638/

Nomenclature

a	First order volume correction to γ_0
B	Intercept of the shock velocity – particle velocity curve
C	Normalization constant
c	Acoustic velocity in water
d	Water film width
d^*	Dimensionless water film width
E	Internal energy
h	Smoothing length which varies in time and in space; Minimum value of interparticle interval
h	Water film depth
l	Water film length
l^*	Dimensionless water film length
L	Perimeter of tire
m	Mass of particle
N	Number of particles in the influence domain of particle i or j
n	Number of SPH particle layers in the water film
p	Pressure
r	Radius of tire
S_1, S_2, S_3	Coefficients of the slope of the shock velocity – particle velocity curve
t	Time
T	Tire rolling period
th	Chine thickness
v	Velocity
V	Relative volume
V	Tire speed
W	Kernel function
w	Distance between the chine outside edge and tire sidewall
W_t	Tire width
x	Location of particle
x, y, z	Ground coordinate system
x', y', z'	Tire coordinate system
α	Angle between side-spray upper edge and ground when viewed from front
α_1	Angle between the upper boundary of the major spray region and the horizontal line
α_2	Angle between the upper boundary of the airflow influence region and the horizontal line
β	Angle between side-spray upper edge and ground when viewed from side
γ	Angle between side-spray outer edge and tire sidewall when viewed from above
γ_0	Gruneisen gamma
θ	Function
$\mathrm{\theta}$	Chine angle, i.e. the angle between the lower edge of linear chine and the horizontal line
$\mathrm{\theta}'$	Arc chine angle, i.e. the angle between the tangent of the arc chine at the outer end point and the horizontal line
μ	Compression
ρ	Density
ρ_0	Initial density
σ	Total stress tensor
υ	Kinematic viscosity of water
Δt	Time step

Subscripts

i, j	Particle codes

Superscripts

α, β	Space indices
d	Number of space dimensions

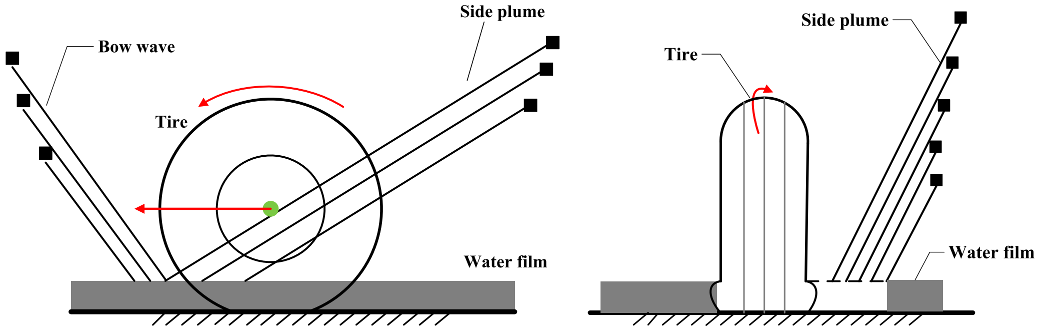

Fig. 1. Sketches of the tire-generated water spray.

experimental method, all the above researches did not investigate the flow physics of tire-generated water spray.

Besides water spray flight test and laboratory experiment, there are some simple methods [2,10] to give a first rough estimate of the location of the tire-generated water spray. The ESDU [10] proposed an engineering estimation method, which is based on a datum derived from both full-scale and model-test data, to estimate the spray patterns generated from the sides of aircraft tires running in water or slush. However, these methods are only capable of giving a first rough estimate of the location of the spray and no information can be obtained on water flow rates.

The reported numerical researches relating to the aircraft tire-generated water spray are scanty due to the complexity of this problem. Trapp and Oliveira [11] simulated the effect of water spray on the EMB-170 aircraft with thrust reverser deployed. They obtained a spray pattern around the fuselage that agreed well with the experimental photos. However, no details of the numerical method and quantitative results were given in their paper. Gooden [12] developed a method based on droplet trajectory calculations, named ‘CR-Spray’, for calculating the spray generated by tires on water-contaminated runways and the subsequent precipitation drag and engine ingestion. The initial conditions for these trajectories are based on (semi)empirical relations derived from ESDU engineering method [10], data in model experiments [5,6,9], flight tests by Dassault (Falcon 2000) [13], Saab (SAAB 2000) [14] and NLR (Cessna Citation II) [15,16]. Qu et al. [17] numerically simulated the water spray caused by a rolling airplane tire by the Smoothed Particle Hydrodynamics (SPH) method. They gave the whole spray process and the effects of tire forward speed and water film thickness on water spray. Zhao et al. [18] proposed an