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ANALYSIS OF THE WIND COVERAGE FACTOR FOR AIRPORT RUNWAYS COMPUTED WITH DIFFERENT PROBABILITY DISTRIBUTIONS

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ABSTRACT
In airport planning, to determine runway orientation and to evaluate the need of an additional runway, it is very important to know the wind direction and its intensity over the time. During the planning stage, for airport site selection, the wind data could not be available. Only the annual average intensity of the wind for each direction is usually known. When this occurs, it is necessary to know the function of wind distribution or, if it is not available, to assume a function to model the wind distribution. In this work the fitness of the Rayleigh and Uniform distributions to wind data measured in a place, and its influence on the wind coverage factor are compared and analyzed.

1 INTRODUCTION

The airport master plan is the planner´s concept of the long-term development of an airport. The master plan is prepared to support the modernization of existing airports and the creation of new airports, regardless of size, complexity, or role, according to the Advisory Circular 150/5070-6A (1985). The airport planning process involves collecting data, forecasting demand, determining facility requirements and developing plans and schedules. The master plan elements are: existing conditions and issues, aviation demand forecasts, requirements of analysis and concepts development, airport size selection, environmental procedures and analysis, simulation, airport plans and plan implementation.

On the preliminary stages of airport design, in order to determine the runway orientation and the rate of utilization for a new airport and to evaluate the necessity of an additional runway for an existing airport, the time history of wind direction and velocity must be known. Other weather conditions and factors, e.g. fog, ceiling, rain, snow, obstacles, airspace, also have an important effect on airport operations, runway location and orientation, capacity and delay. These factors are not evaluated in this paper.

Airport planners and designers must make an accurate wind analysis to determine the orientation and number of runways. A proper application of the results of this analysis will add to the safety and the capacity of the airport. This analysis is based on the determination of an index denominated "wind coverage factor". This factor is the percentage of time that the crosswind components are below a specified velocity. The crosswind is the component of the wind velocity vector perpendicular to the runway. The most desirable runway orientation based on wind analysis is the one with the highest wind coverage factor. In accordance to Annex 14, Volume I, of the International Civil Aviation Organization (ICAO, 1996) the recommendable wind coverage for an airport is not less than 95%. The crosswind velocity limits depend on the particular aircraft takeoff distance. These are grouped in three classes, as shown in Table 1.

Table 1 : Limits of crosswind velocity

Crosswind velocity	Takeoff distance (ISA)
37 km/h (20 knots)	Over 1500 m
24 km/h (13 Knots)	Between 1200 m and 1500 m (exclusive)
19 km/h (10 knots)	Under 1200 m

The wind coverage factor is usually calculated graphically from the wind rose, which is the typical graphical presentation of the wind information. It consists of series of concentric circles and radial lines. Each concentric circle represents the division between successive wind velocity groupings. The numbers in each sector represent the percentage of probability of wind velocity between two values for the sector wind direction.

When only the wind rose is known, the classical analysis procedure to determine the wind coverage factor presumes that the wind velocity is uniformly distributed over the area represented by each segment of the wind rose, according to Advisory Circular 150/5300-13 (1989).

During the planning stage, for airport site selection, the wind data could not be available. Sometimes the annual average wind velocity for each direction is the only parameter known. When this occurs, it is necessary to know the wind probability distribution or, if it is not available, to assume a function to fit this distribution.

The objective of this work is to compare and analyze the results of modeling the wind data measured in a place with two distributions, and their influence in the determination of the wind coverage factor.

2 ANALYSIS OF WIND DATA

Different probability distributions can be used to model the wind velocity, corresponding to a place or area, over a defined period. When time series of wind velocity values are known, the Weibull function is accepted as the best model to fit the wind distribution (Oliva, R., 1997). It has been used widely, both for wind velocity and wind energy analysis. Furthermore, researchers involved in wind velocity analysis have employed for many years the Weibull distribution. The meteorological data indicate the amount of the wind that blows from each direction. The most usual index for the wind intensity is the average velocity (V_{avg}). The mathematical definition of this average is given by

$$v_{avg} = \int_0^\infty v\ f(v)\ dv \qquad (1)$$

Where v is the random variable and $f(v)$ is the probability distribution function. When only the wind average velocity is known, it is necessary to assume an approximate expression to describe the wind distribution. The Rayleigh function, as a particular case of the Weibull distribution, is an adequate model to fit the wind velocity distribution for describing wind in low turbulence sites. The wind velocity can also be modeled with the more simple Uniform distribution. ICAO recommends this distribution when the wind data is not available.

3 PROBABILITY DISTRIBUTION FOR WIND VELOCITY

The probability density function, the probability of wind velocity between two given values, the cumulative distribution function, the mean velocity and the parameters for the Weibull, Rayleigh and Uniform distributions (Meyer, P., Probabilidades y aplicaciones estadísticas, 1998), are shown in Table 2.

Table 2: Weibull, Rayleigh and Uniform distributions

	Weibull distribution	Rayleigh distribution	Uniform distribution
Probability distribution function	$fw(v)=\frac{k}{A}\left[\frac{v}{A}\right]^{k-1} e^{-\left(\frac{v}{A}\right)^{k}}$ $v, k, A > 0$	$fr(v)=\frac{2}{A}\left[\frac{v}{A}\right] e^{-\left(\frac{v}{A}\right)^{2}}$ $v, A > 0$	$fu(v)=\frac{1}{b-a}$
Probability of wind intensity between two values	$P(v_1 \le v \le v_2) =$ $= \int_{v_1}^{v_2} fw(v)\, dv =$ $= e^{-\left(\frac{v1}{A}\right)^{k}} - e^{-\left(\frac{v2}{A}\right)^{k}}$	$P(v_1 \le v \le v_2) =$ $= \int_{v_1}^{v_2} fr(v)\, dv =$ $= e^{-\left(\frac{v1}{A}\right)^{2}} - e^{-\left(\frac{v2}{A}\right)^{2}}$	$P(v_1 \le v \le v_2) =$ $= \int_{v_1}^{v_2} fu(v)\, dv =$ $= \int_{v_1}^{v_2} \frac{1}{v_{max} - v_{min}}\, dv$
Cumulative distribution function	$Fw(v) = 1 - e^{\left(\frac{v}{A}\right)^{k}}$	$Fr(v) = 1 - e^{\left(\frac{v}{A}\right)^{2}}$	$Fu(v) = \frac{v - v_{min}}{v_{max} - v_{min}}$
Mean	$v_{mean} = A\Gamma\left(1+\frac{1}{k}\right)$	$v_{mean} = A\Gamma\left(1+\frac{1}{2}\right) = A\frac{\sqrt{\pi}}{2}$	$v_{mean} = \frac{v_{max}}{2}$
Parameters	This distribution has two parameters: k, the nondimensional shape or form factor, and A, the scale factor, with velocity dimensions.	The Rayleigh distribution is a special and simplified case of the Weibull probability, with k = 2. It has only one parameter, A, or scale factor, has units of wind velocity.	This distribution has two parameters: b, the highest wind velocity (v_{max}), and b, the , lowest wind velocity (v_{min}).

4 WIND VELOCITY DISTRIBUTION MODELS

When only the average velocity from each direction is known, it is not possible to fit a Weibull function to the wind distribution, because the data are not sufficient to determine both parameters A and k. On the other hand, it is possible to model the wind distribution using the Rayleigh or the Uniform functions, with some hypothesis.

4.1 Parameters for the Rayleigh distribution

The variable intensity of wind (v) is defined in the interval [0, ∞].

The arithmetic average velocity calculated from the measured velocity of wind (v_{avg}) is the best estimate of the mean velocity (v_{mean}), this leads to:

$$A = v_{mean}\frac{2}{\sqrt{\pi}} = v_{avg}\frac{2}{\sqrt{\pi}} \tag{2}$$

4.2 Parameters for the Uniform distribution

The lowest wind velocity is equal to zero.

The arithmetic average velocity calculated from the measured velocity of wind (v_{avg}) is the best estimate of the mean velocity (v_{mean}), this leads to:

$$v_{max} = 2\, v_{mean} = 2\, v_{avg} \quad (3)$$

The variable velocity of wind (v) is defined in the interval [0, v_{max}].

5 WIND DATA ACQUISITION

The wind data have been measured in the suburban area of La Plata city, Argentina, in the campus of Astilleros Rio Santiago (34º 52´ S, 57º 54´ W). The wind direction and intensity have been measured with a 3-cup anemometer and an arrow shaped wind vane meteorological station. The station has been placed on a 10 m high tower in an open terrain. In addition to the wind, the outside temperature, humidity and atmospheric pressure have also been measured. The meteorological station wind velocity range is 0 to 180 km/h, with a resolution of 1.8 km/h. The range for the wind direction is 0 to 360 degrees, with a resolution of 22.5 degrees. The wind data have been acquired every 15 s, averaged over 15 min and stored in a data logger. The data have been adquired from september to december 2003. The wind data have been grouped in 16 directions, and the wind intensity data have been grouped in 5 intervals. The stored data in time series format have been processed to obtain a histogram for each direction, with class intervals in accordance to the crosswind limits needed to evaluate the coefficient of wind coverage for runways (0-19 , 19-24 , 24-37 and 37-v_{max} km/h). As an example, the experimental results and the calculated probability from the Rayleigh and the Uniform functions for north, east, south and west directions are shown in Tables 3 to 6.

Table 3 : Observed probability of occurrence, Raleigh and Uniform probability density distributions, for North wind direction

Wind velocity range (km/h)	Observed probability of occurrence (%)	Rayleigh probability distribution (%)	Uniform probability distribution (%)
(0-19]	8.85	4.79	4.43
(19-24]	0.05	1.53	1.16
(24-37]	0.09	2.17	3.03
(37-v_{max}]	0.00	0.50	0.37
v_{max} = 35.3 v_{mean} = 19.3	Σ = 8.99	Σ = 8.99	Σ = 8.99
		Parameter: A = 21.78	Parameters: $a = v_{min} = 0$ $b = v_{max} = 38.6$

Table 4 : Observed probability of occurrence, Raleigh and Uniform probability density distributions, for East direction

Class Interval (km/h)	Observed probability of occurrence (%)	Calculated probability from Rayleigh function (%)	Calculated probability from Uniform function (%)
(0-19]	3.77	5.05	4.67
(19-24]	3.60	1.61	1.23
(24-37]	2.11	2.29	3.19
(37-v_{max}]	0.00	0.53	0.39
v_{max} = 35.3 v_{mean} =19.3	$\sum$ = 9.48	$\sum$ = 9.48	$\sum$ = 9.48
		Parameter: A = 21.78	Parameters: $a = v_{min} = 0$ $b = v_{max} = 38.6$

Table 5 : Observed probability of occurrence, Raleigh and Uniform probability density distributions, for South direction

Direction S				
Interval	Class Interval (km/h)	Observed probability of occurrence (%)	Calculated probability from Rayleigh function (%)	Calculated probability from Uniform function (%)
1	(0-19]	6.83	6.75	6.01
3	(19-24]	2.31	1.72	1.58
4	(24-37]	1.30	1.82	2.91
5	(37-v_{max}]	0.07	0.21	------
	v_{max} = 46.8 v_{mean} =16.6	$\sum$ = 10.51	$\sum$ = 10.51	$\sum$ = 10.51
			Parameter: A = 18.73	Parameters: $a = v_{min} = 0$ $b = v_{max} = 33.2$

Table 6: Observed probability of occurrence, Raleigh and Uniform probability density distributions, for West direction

Direction W				
Interval	Class Interval (km/h)	Observed probability of occurrence (%)	Calculated probability from Rayleigh function (%)	Calculated probability from Uniform function (%)
1	(0-19]	1.93	2.01	2.07
3	(19-24]	0.07	0.05	-----
4	(24-37]	0.07	0.01	-----
5	(37-v_{max}]	0.00	0.00	-----
	v_{max} = 28.8 v_{mean} =8.9	$\sum$ = 2.07	$\sum$ = 2.07	$\sum$ = 2.07
			Parameter: A = 10.04	Parameters: $a = v_{min} = 0$ $b = v_{max} = 17.8$

The summary of wind velocity probability of occurrence and its calculated probability from the Rayleigh and the Uniform functions for each direction is shown in Fig. 1.

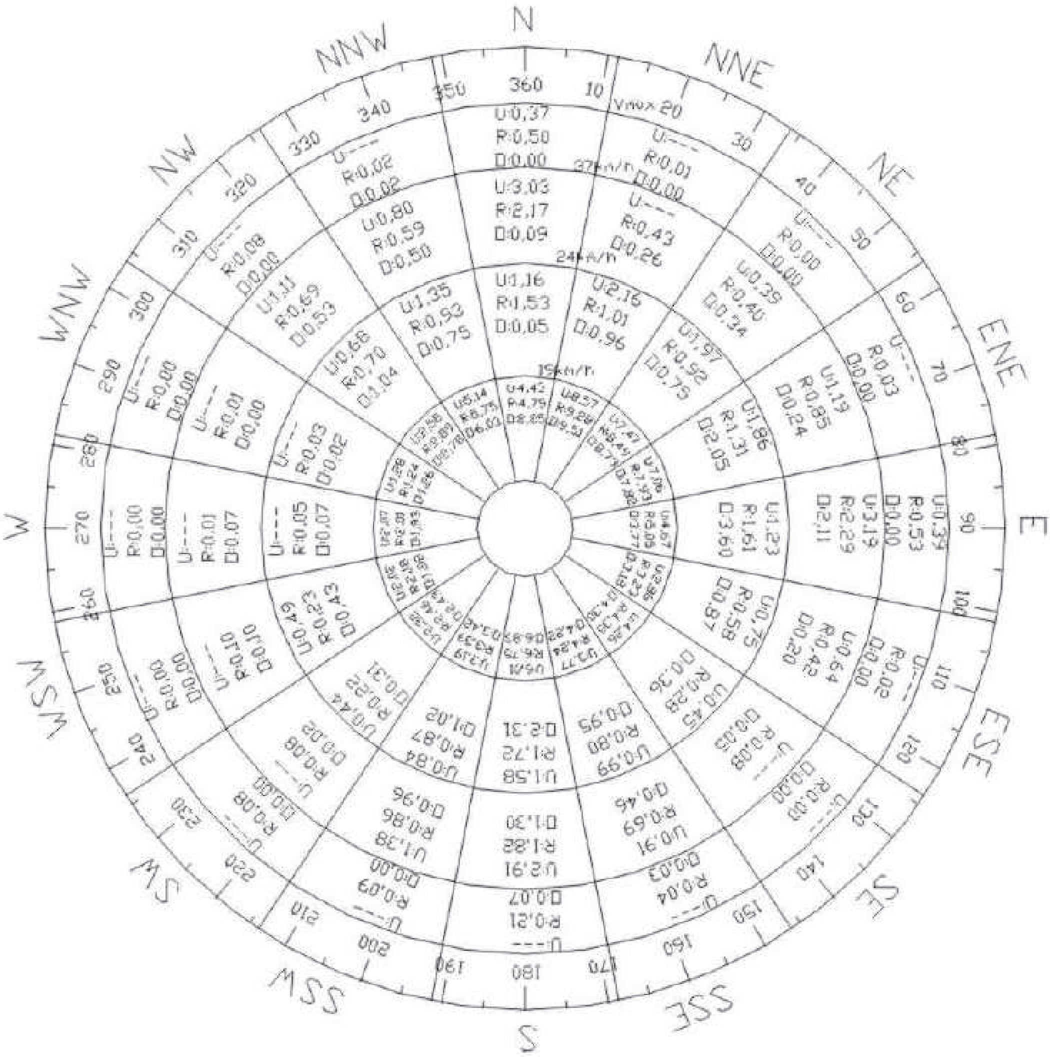

Figure 1: Wind rose. Observed (O) probability of occurrence and calculated probability from Rayleigh (R) and Uniform (U) functions, by direction

6 WIND COVERAGE ANALYSIS

The real wind coverage factor calculated with the time series of values is shown in Table 7. This analysis gives a runway oriented to a magnetic azimuth of 259 - 79 degrees (runway designation marking of 26 – 08).

The wind coverage factor using the Rayleigh and Uniform distributions have also been calculated from the wind rose. The results are given in Table 7.

Table 7 : Wind coverage factor

Limit of crosswind velocities (km/h)	Observed wind coverage factor (%)	Calculated wind coverage factor using Rayleigh function (%)	Calculated wind coverage factor using Uniform function (%)
19	89.8	85.3	82.3
24	96.5	92.7	90.7
37	99.6	99.2	99.7

The analysis has been carried out for the three limits of crosswind velocities specified in Aerodrome Design Manual. Part 1. Runways (ICAO, 1996).

7 CONCLUSIONS

From the wind data measurements, the real wind coverage factor has been calculated. This has been compared with the wind coverage factors determined from the Rayleigh and Uniform distributions. The analysis of the measured wind data shows that it is possible to satisfy the 95% coverage factor for crosswind velocities of 24 and 37 km/h with only one runway. For the 19 km/h crosswind criteria an additional runway would be needed.

The calculated wind coverage factor computed by the Rayleigh and Uniform functions gives, for a 24 km/h crosswind velocity, a wind coverage factor less than 95%. Then it would be necessary to provide an additional runway, in order to achieve, with the combination of both, the required wind coverage by this criterion.

The Uniform distribution underestimates the real wind coverage factor by as much as 7% for the limits 19 km/h and 24 km/h of crosswind velocities. It is very important to make a precise analysis, to determine whether the construction of two runways would be necessary or not. If the theoretical analysis gives the requirement of two runways, it is necessary to collect experimental wind data to validate the theory.

The Uniform distribution is more likely to lead to the need of an additional runway, in what could be a design mistake. For this analysis, the Rayleigh distribution is still being conservative, because it underestimates the wind coverage factor for the three crosswind limits, and approximates better than the Uniform distribution the real wind coverage factor, with practically no additional mathematical difficulty. Of course, the effort should be directed to obtain time series of wind data from one or several years.

It is worth to mention that in other analyzed cases, the Rayleigh distribution has overestimated the wind coverage factor by as much as 3%, particularly when the average wind velocities are high. The Uniform distribution has always underestimated the wind coverage factor by about 7%; and in some cases, by 20%.

Finally, for preliminary analysis, when only the average wind velocities and directions are available, the Uniform distribution shows to be always conservative. The Rayleigh distribution shows to be more precise, but it could overestimate the wind coverage factor. It would be a good choice to determine the wind coverage factor with both distributions simultaneously.

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