**Empirical models for the structure-borne sound power input from artificial and natural rainfall**

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**Abstract**

Interpretation and application of laboratory rain noise measurements using artificial rain on roof elements of buildings and cars requires validated prediction models for the structure-borne sound power input during artificial and natural rainfall. Empirical models have therefore been developed for the time-dependent force on horizontal and inclined plates with artificial and natural rainfall. For inclined plates, two approaches have been developed. The first approach uses the empirical model for a horizontal plate (dry or with surface water) and converts it to an inclined plate by estimating the drop velocity in the direction perpendicular to the plate surface. The second approach extends a semi-empirical model for dry, horizontal plates so that it applies to drops falling at terminal velocity onto dry, inclined plates. Experimental work was carried out to validate these models. Measurements for single 4.5 mm drops impacting on plates inclined up to 60° showed better agreement with the second approach. Artificial rain measurements for rainfall rates between 24 and 30 mm/h confirmed the validity of this second approach even though it assumes a dry surface. However, for heavy and torrential rain (i.e. rainfall rates higher than 40 mm/h), the first approach to modelling allows the option to include a 1 or 2 mm water layer on the surface. The validated model for the second approach has been used to calculate conversion factors between laboratory measurements with artificial rain to other situations with natural or artificial rainfall, and between measurements on roof elements that are inclined at different angles.

**1. Introduction**

Rain falling on a skylight or the lightweight roof of a building can significantly increase the background noise inside the room underneath it. A similar situation occurs inside car cabins due to rain falling on a panoramic glass roof, multilayer metal roof, or the front and rear windscreens. At the design stage, it is useful to predict the radiated sound due to natural rainfall because increased noise levels can adversely affect speech intelligibility, comfort and listening conditions for the occupants. However, the rainfall rate during natural rain varies over time and has a statistical distribution of raindrop diameters. This is complex to simulate in laboratory tests; hence, artificial rain is used in laboratory set-ups. Therefore, it is necessary to convert laboratory measurements so that they represent aspects of natural rainfall in the field situation. This requires estimates of the force applied by raindrops and the power input from artificial and natural rainfall as an input parameter for prediction models of sound transmission and sound radiation, for example, Statistical Energy Analysis (SEA) (e.g. see [[[1]](#endnote-1)], and the Transfer Matrix Method (TMM) (e.g. see [[[2]](#endnote-2)]). These issues are addressed in this paper.

**1.1 Rain noise measurement**

Laboratory measurements can be used to assess the sound radiated by roof elements; this is often essential when the construction is relatively complex and its structural dynamics cannot be modelled with sufficient accuracy. Early experimental work on rain noise by Dubout [[[3]](#endnote-3)] used natural rainfall falling on the steel profiled roof of a small shed, although the roof pitch was not stated. This resulted in an empirical relationship between the radiated sound intensity and rainfall rate for one specific type of steel roof. Subsequent laboratory measurements began to use artificial rain, which provided greater control over the rainfall properties. Ballagh [[[4]](#endnote-4)] used artificial rain from pressurised water ejected from a nozzle to give rainfall rates between 17 and 95 mm/h with drop velocities below terminal velocity. This established that the factor relating the logarithm of rainfall rate to radiated sound intensity was similar to Dubout’s relationship for natural rain. Tests on nine different roofing systems (roof pitch was 3°) with a rainfall rate of 80 mm/h were used to rank order the roofs in terms of the A-weighted radiated sound intensity, Speech Interference Level (SIL) and Noise Criteria (NC). To predict rain noise, Ballagh used the equations from Petersson [[[5]](#endnote-5)] to estimate the force applied by an idealised drop shape. However, the comparisons with measurements were inconclusive; this was partly due to the complexity in modelling vibration transmission across the lightweight roof constructions. Suga and Tachibana [[[6]](#endnote-6)] created artificial rainfall using pressurized water and multiple nozzles to give heavy to torrential rain conditions (4 and 5 mm drop diameters with rainfall rates of 30 and 60 mm/h respectively) but with drop velocities below terminal velocity. Their measurements on lightweight roof constructions established a linear relationship between the sound transmission loss and the radiated sound power with artificial rain (in a similar way to floors where there is a relationship between the impact sound insulation measured with the tapping machine and the transmission loss).

McLoughlin et al. [[[7]](#endnote-7)] created artificial rain using a ‘rain box’ (i.e. a header tank with a perforated base) which produced 4.6 or 5.5 mm drop diameters at rainfall rates between 72 and 300 mm/h. Drop heights varied from 0.5 to 4.43 m but there was not sufficient height to achieve terminal velocity. Their laboratory measurements on a single-skin metal roof were not intended to represent natural rainfall, but to produce sound pressure levels well-above background noise such that an empirical correction could be developed to estimate the radiated sound for natural rain. An empirical relationship was derived between the A-weighted sound intensity level, rainfall rate, drop velocity and drop diameter. Using this relationship, in conjunction with a graph corresponding to natural rain that followed the Marshall-Palmer distribution of raindrops, it was proposed that any laboratory measurement with known artificial rain could be used to estimate the response to natural rain. The roofs had a different pitch in two directions (≈10° and ≈20°) but no indication was given as to whether pitch was important and whether the rain box (1 m2 coverage area) was used in more than one position. Yan et al. [[[8]](#endnote-8)] also sought to experimentally determine a relationship between artificial and natural rainfall. A series of tests on a double-layer metal skin roof (≈1° pitch) were carried out when excited by artificial and natural rainfall. Similarly to McLoughlin et al. this gave an empirical relationship between the A-weighted sound level, rainfall rate, fall height (i.e. drop velocity) and drop size distribution.

Laboratory measurements of the radiated sound power due to artificial rain on building elements are described in the International Standard, ISO 10140-5 [[[9]](#endnote-9)]. This prescribes use of a rain box to produce two types of artificial rainfall for measurements; these are ‘intense’ and ‘heavy’ rain which have rainfall rates of 15 and 40 mm/h respectively, and median drop diameters of 2 and 5 mm respectively. The previous measurement standard, ISO 140-18 [[[10]](#endnote-10)], also defined ‘moderate’ rain as having a rainfall rate of 4 mm/h [[[11]](#endnote-11)] and a 0.5 to 1 mm drop diameter but this was not intended for measurements because sound pressure levels would not always be measurable for highly insulated roofs. It has also been noted that the description of the rain box in ISO 10140-5 is not sufficient to ensure uniformity of drop diameters for heavy rain [[[12]](#endnote-12)]. For the roof element under test, ISO 10140-5 refers to a pitch of 30° as the standard configuration. Whilst 30° is a reasonable value for the average roof pitch, roofs on buildings tend to be inclined at angles between 5° and 75°. However, flat roofs exist on cars and on some buildings and the effect of the angle on the power injected into a plate by rain has not yet been established.

**1.2 Prediction of rain noise**

Due to the complexities in arranging laboratory tests, an alternative approach has been to investigate the prediction of rain noise in buildings. The prediction of the radiated sound can be considered in two stages, firstly the structure-borne sound power input into the upper surface of the element from the rainfall, and secondly the sound transmission and radiation model. To predict the power input, models are required for the time-dependent force applied by the impact of a liquid water drop on a plate. Petersson [5,[[13]](#endnote-13)] developed idealized models based on paraboloidal and cylindrical–hemispherical drop shapes impacting a dry, rigid, horizontal plate. These were validated using drop velocities below terminal velocity, which could have represented artificial rain. Based on Petersson’s early work, Ballagh [4] used the cylindrical–hemispherical model. However, for drop velocities below terminal velocity, Petersson [13] later showed that the paraboloidal model gave closer agreement with measurements than the cylindrical–hemispherical model. For this reason the paraboloidal model was used by Suga and Tachibana [6] when trying to gain insights into their measurements with artificial rain and by Guigou-Carter and Villot [2] to develop sound transmission and radiation models that would extend the prediction of laboratory measurements of rain noise to complex multi-layered systems (e.g. double glazing, double-layer metal skin roof). Comparison of artificial rain measurements on a double-layer metal skin roof indicated reasonable agreement in the mid- and high-frequency ranges but not in the low-frequency range.

Petersson’s idealised drop shape models were only assessed at sub-terminal drop velocities and his initial experiments into the effect of a surface layer of water did not indicate the depth of the layer or the drop velocity. For this reason, Yu and Hopkins [[[14]](#endnote-14)] developed a more accurate experimental approach using wavelets to measure the time-dependent force for a range of drop velocities up to and including terminal velocity. These results were used to develop empirical models for the force from drop impacts on horizontal plates that are dry or have a shallow water layer. The intention was that these models could be applied to artificial and natural rain. Having analysed the form of the measured time-dependent force, Yu and Hopkins adopted empirical equations that were in a similar form to a probability density function for a lognormal distribution; this could reproduce the initial rapidly rising force, the peak force and the exponential decay. Mitchell et al. [[[15]](#endnote-15)] subsequently proposed a semi-empirical model for spherical drop impacts on a dry surface at sub-terminal drop velocities which incorporates a similar exponential decay.

For 2 and 4.5 mm drops impacting on a dry, horizontal surface at terminal velocity, Fig. 1 allows comparison of the wavelet measurement, the empirical model from Yu and Hopkins, Petersson’s idealised models for the paraboloidal and cylindrical–hemispherical drop shapes and Mitchell et al’s model. In the time domain, the measured peak force for 2 mm drops is close to the empirical model from Yu and Hopkins as well as models from Petersson and Mitchell et al. However, the measured peak force for 4.5 mm drops is significantly higher than the models from Petersson and Mitchell et al. but is close to the empirical model from Yu and Hopkins. In the frequency domain, the difference for all models is uniform at low frequencies and increases at higher frequencies.

For all models, the 4.5 mm drops have <1 dB difference up to 800 Hz, with the largest difference being 10.7 dB at 3k Hz for the cylindrical–hemispherical model and ≈8 dB at 5k Hz for the paraboloidal and the semi-empirical models. For all models, the 2 mm drops have ≈2 dB difference up to 600 Hz, with the largest difference being 4.8 dB at 5k Hz for the cylindrical–hemispherical model and 2.8 dB at 3.15k Hz for the paraboloidal model. In contrast to the models from Petersson and Mitchell et al., the differences in the empirical model from Yu and Hopkins are significantly lower (≤1.1 dB for the 4.5 mm drop and <2 dB for the 2 mm drop across the entire frequency range) and the models have a wider application because they were not only developed for dry plates, but also for water layers up to 10 mm deep on top of a plate. The empirical model from Yu and Hopkins has higher accuracy because it was developed using measurements with drops travelling at terminal velocity; Petersson only validated his model at sub-terminal velocities and Mitchell et al. used experimental data at sub-terminal drop velocities to derive empirical constants for the model. In addition, Mitchell et al. only considered spherical drops which are unrepresentative of drops at terminal velocity for which drop diameters ≥2 mm will have a flattened bottom; these can be described as ellipsoidal in shape [[[16]](#endnote-16)]. Whilst an ellipsoidal model is potentially more suitable, a previous assessment of this idealised drop shape model did not lead to correct estimates of the peak force at terminal velocity [14].

**1.3 Aims**

This paper aims to develops empirical models for artificial and natural rain that can be used to: (a) predict the power input for different rainfall rates representing artificial and natural rainfall, (b) assess the validity of a laboratory facility for measuring rain noise from artificial rain, and (c) convert any laboratory measurement with artificial rain, to any other situation with natural or artificial rainfall. Whilst flat roofs occur in some buildings and cars, the majority of practical situations involve plates at different inclined angles and with some surface water on the plate; hence these issues are considered in this paper.

**2. Empirical models for the time-dependent input force from artificial and natural rainfall**

The empirical models that were previously developed by the authors for drop impacts on horizontal plates are summarised in Section 2.1 as these provide the basis to develop new models in Section 2.2 for inclined plates.

Section 2.1.1 describes the empirical models from Yu and Hopkins [14] for 2 and 4.5 mm drops impacting upon a horizontal plate for application to artificial rainfall generated in the laboratory for measurements according to ISO 10140-5. Note that ISO 10140-5 uses 2 and 5 mm diameter drops but it is reasonable to assume that there are negligible differences between 4.5 and 5 mm. For brevity in the text, drops are referred to as ‘*X* mm drops’ where *X* corresponds to the equivalent drop diameter. Section 2.1.2 then gives models for artificial rainfall (2 and 5 mm drops) falling at terminal velocity and Section 2.1.3 extends these models to natural rainfall.

For inclined plates, Section 2.2.1 develops an approach which allows the drop velocity to be modified to represent the component of the drop velocity that is perpendicular to the plate surface whilst still using the empirical models from Yu and Hopkins that were described in Section 2.1; this is referred to as the ‘angle-corrected empirical model’. An alternative approach is developed in Section 2.2.2 by modifying a model from Mitchell et al. [15] so that it also applies to drop impacts at terminal velocity and for inclined plates; this is referred to as the ‘angle-corrected semi-empirical model’.

**2.1 Horizontal plates**

For horizontal plates, this section describes calculation of the time-dependent force from (1) artificial rain as described in ISO 10140-5 for a single rainfall rate and a single raindrop diameter with drop velocities below terminal velocity, (2) artificial rain for a single rainfall rate and a single raindrop diameter with drops impacting at terminal velocity, and (3) natural rain for a single rainfall rate and drop distributions given by the Marshall-Palmer distribution with all drops impacting at terminal velocity.

**2.1.1 Artificial rain (ISO 10140-5)**

In many laboratories it is unusual to have sufficient headroom to elevate the rain box to a height which would provide drop impacts at terminal velocity, i.e. 6.6 m to give 6.2 m/s for 2 mm drops and 12 m to give 9.5 m/s for 5 mm drops (estimated from [14]). For this reason, ISO 10140-5 currently prescribes a fall height of ≈1 m to achieve 4 m/s for 2 mm drops (artificial intense rain) and a fall height of ≈3.5 m to achieve 7 m/s for 5 mm drops (artificial heavy rain).

From Yu and Hopkins [14], the following empirical formula describes the time-dependent force, *f*(*t*), from a drop impact over time, *t*, using a three-parameter model (*C*A, *α*A, *β*A):

|  |  |
| --- | --- |
|  | (1) |

For a drop velocity, *v*d, that is lower than terminal velocity, *C*A, A and *β*A can be calculated using the following three equations with the empirical constants (*aC, bC, aα, bα, aβ, bβ*) given in Tables 1 and 2 for drops impacting below terminal velocity onto a plate with or without a water layer.

|  |  |
| --- | --- |
|  | (2) |
|  | (3) |
|  | (4) |

where *v*d is the drop velocity (when lower than terminal velocity) which can be calculated using the empirical equation provided by Range and Feuillebois [[[17]](#endnote-17)] with a friction coefficient, *c*f=0.533 determined by Yu and Hopkins [14]:

|  |  |
| --- | --- |
|  | (5) |

where *g* is the acceleration due to gravity (m/s2), *H* is the fall height (m) and

|  |  |
| --- | --- |
|  | (6) |

in which *D* is the equivalent drop diameter (mm), *ρ*a is the density of air (kg/m3) and *ρ*w is the density of water (kg/m3).

**2.1.2 Artificial rain at terminal velocity**

This section describes calculation of the time-dependent force for artificial rain at terminal velocity as this is required for experimental validation of the conversion of any laboratory measurement with artificial rainfall to one with a different type of artificial rainfall.

For 2 mm drops, the time-dependent force for a drop impacting at terminal velocity onto a plate with or without a water layer can be calculated using Eq.(1) with the empirical constants in Table 3 [14].

For 5 mm drops, the time-dependent force for a drop impacting at terminal velocity onto a plate with or without a water layer can be calculated using [14]

|  |  |
| --- | --- |
|  | (7) |

where *C*A*i*, *α*A*i* and *β*A*i* (*i*=1,2) are empirical constants given in Table 4; these values correspond to measurements on 4.5 mm drops but the difference is considered to be negligible. Note that *C*A2=0 when there is no water layer; hence Eq.(7) only uses the second term when there is a water layer.

**2.1.3 Natural rain at terminal velocity**

For natural rain, it is assumed that all drops impact at terminal velocity, *v*T in m/s, which can be calculated using the empirical equation from Best [[[18]](#endnote-18)]:

|  |  |
| --- | --- |
|  | (8) |

Natural rain has a statistical distribution of drop diameters which can be modelled using the Marshall-Palmer distribution in terms of *n*(*D*) in mm-1m-3 as given by [[[19]](#endnote-19)]

|  |  |
| --- | --- |
|  | (9) |

where *R*r is the rainfall rate (mm/h).

Note that whilst a gamma distribution has also been proposed for drop size distributions, the Marshall-Palmer distribution is still considered to be robust [[[20]](#endnote-20)] and can be considered sufficiently accurate for larger drop diameters that primarily determine rain noise. Figure 2 shows the Marshall-Palmer distribution for three different rainfall rates (4, 15 and 40 mm/h) which indicates how the number of larger diameter drops increases with increasing rainfall rate. Note that whilst 6 mm drop diameters are shown on this figure there is rarely a need to consider drop diameters larger than 5 mm in temperate climates because any larger drops tend to break up into smaller drops as they descend from the clouds [[[21]](#endnote-21)]. All calculations for natural rain in this paper carry out calculations assuming that the largest drop diameter is 5 mm.

The time-dependent force for any drop diameter impacting at terminal velocity onto a plate with or without a water layer can be calculating using the following general equation which takes a similar form to Eqs. (1) and (7):

|  |  |
| --- | --- |
|  | (10) |

where *C*N*i*, *α*N*i* and *β*N*i* (*i*=1,2) are empirical constants.

As natural rain consists of a range of different drop diameters, the empirical constants now need to be determined for any diameter drop falling at terminal velocity. When comparing forces with different diameter drops and different drop velocities in [14] it is common to normalize the measured force to 10-6*ρ*w*v*d2*D*2, in order to give a dimensionless force (e.g. [[[22]](#endnote-22)]). Therefore, it is assumed that the extension of *C*N1 to any drop diameter at terminal velocity will be a second-order polynomial function with respect to *v*d2*D*2. The first step is to note that for 0 mm drops, the amplitude of the force must be set to zero, Hence by combining this requirement with the empirical constants that were previously determined for 2 and 4.5 mm drops, Eq.(10) can be extended to all drop diameters above 0 mm up to 6 mm. In the absence of information on drop diameters other than 2 and 4.5 mm drops, the available data on 2 and 4.5 mm drops at different drop velocities [14] was used to carry out a second-order polynomial curve fit on *C*N1 for 2 and 4.5 mm drops with respect to *v*d2*D*2. The parameters in Eq.(10) are obtained by minimizing the term, where *i* is the index of the measurement, *i*=0 is the terminal velocity measurement and *i≠*0 indicates velocities below terminal velocity. The main aim is to provide a model for terminal velocity; hence to weight the data towards terminal velocity, , is used where  is the Dirac function. Figure 3 shows the available data as blue and red solid lines for 2 and 4.5 mm drops respectively with black dash-dot lines and black dashed lines corresponding to the second-order polynomial curve fit for 2 and 4.5 mm drops respectively. This gives the constant *C*N1 as:

|  |  |
| --- | --- |
|  | (11) |

where *C*a1, *C*a2, *C*b1, *C*b2 and *C*b3 are given in Table 5.

Assuming a linear relationship between *v*T2*D*2 and *α*N1 or *β* N1, and using the data from 2 and 4.5 mm drops at terminal velocity [14] gives:

|  |  |
| --- | --- |
|  | (12) |

|  |  |
| --- | --- |
|  | (13) |

The empirical constant, *C*N2 is primarily needed for drop diameters in the range, 2.5 mm ≤ *D* ≤ 6 mm, on a thin water layer for which a linear relationship is proposed based on the 4.5 mm drop data:

|  |  |
| --- | --- |
|   | (14) |

where *K*4.5mm, *α*N2, and *β*N2 are given in Table 5.

The time-dependent forces for different drop diameters using this natural rain model are shown on Fig. 4(a) in the time domain in terms of the dimensionless force against dimensionless time, and on Fig. 4(b) in the frequency domain. The suitability of the regression analysis with this empirical model is assessed through comparison with measured data from 2 and 4.5 mm drops on a dry glass plate [14]. This shows that in the frequency-domain, the differences between the measurements and the model are <1.5 dB for 2 mm drops and <1 dB for 4.5 mm drops; hence the model is considered to be reasonable.

**2.2 Inclined plates**

Two approaches are proposed for inclined plates. The first approach described in Section 2.2.1 is to convert the time-dependent force calculated for a horizontal plate (according to the empirical models from Section 2.1) to an inclined plate by estimating the drop velocity in the direction that is perpendicular to the plate surface. The second approach is to modify the model from Mitchell et al. [15] for dry plates so that it provides a relatively simple equation to calculate the response on a dry inclined plate; this is described in Section 2.2.2.

**2.2.1 Angle-corrected empirical model**

The time-dependent force on a horizontal plate that was calculated according to Sections 2.1.1, 2.1.2 and 2.1.3 for artificial and natural rain can be modified for a plate that is inclined at an angle, *θ*, as indicated in Fig. 5.

For a spherical drop shape impacting at a low velocity (i.e. well-below terminal velocity), Zhang et al. [22] have shown that that the component of the drop velocity, *v*d,n, that is perpendicular to the plate surface primarily determines the impact force pulse that is applied to the inclined plate. They also showed that the spreading velocity during the initial phase of the impact is larger than the tangential component of the impact velocity, *v*d,t. Whilst the tangential component can result in slip motion of the drop on the plate it has little effect on the applied force. However, for 5 mm raindrops at terminal velocity, the drop shape is not spherical and it is expected to be an ellipsoid with a flattened bottom [[[23]](#endnote-23)]. Therefore, the time-varying projection area during the impact process may lead to a more complex time-dependent force profile.

The approach proposed in this paper is to replace *v*d with *v*dcos(*θ*), or *v*T with *v*Tcos(*θ*), in the equations given in Sections 2.1.1 and 2.1.2 for a horizontal plate; this is referred to as the angle-corrected empirical model. The applicability of this approach will be assessed through comparison with experimental data from single drop impacts on a horizontal and inclined dry plate.

**2.2.2 Angle-corrected semi-empirical model**

Mitchell et al. [15] introduced a semi-empirical model for the time-dependent force from liquid drop impacts on a dry, horizontal surface. The empirical constants in the model were determined from measurements using a variety of liquids, including water drops (1.9, 2.9 and 4.7 mm diameters) but only at sub-terminal drop velocities. These measurements were carried out at sub-atmospheric pressure so that the drops remained spherical. However, for 2 and 5 mm drops at the drop velocity used for artificial rainfall measurements according to ISO 10140-5 the drops are expected to be ellipsoidal [23]. Table 6 shows drop axis ratios measured in previous work [14] and estimated according to Beard et al. [16] for different drop velocities. This shows that for 2 and 5 mm drops travelling at terminal velocity (i.e. the situation with natural rainfall), the drops can be considered to be ellipsoidal. The aim is to use the (relatively compact) semi-empirical equation from Mitchell et al. to determine a more flexible model with empirical constants that apply to ellipsoidal-shaped drops falling at any velocity up to and including terminal velocity, onto either a horizontal or inclined dry surface. This will be referred to as an angle-corrected semi-empirical model.

For a horizontal surface, Mitchell et al. [15] proposed the following semi-empirical model

|  |  |
| --- | --- |
|  | (15) |

where *C* and *τ* are empirical constants that were determined using experimental data with spherical drops at sub-terminal drop velocities. The constants were determined by identifying the time to peak force, *t*p, and then setting the time derivative of the force to zero at time, *t*p, to determine a value for *C* that gave the peak force, *f*p.

To create the angle-corrected semi-empirical model, an additional constant, *α*, was incorporated into Eq.(15) to account for the angle of the inclined plate. To ensure that the decay of the time-dependent force after the peak force was correct for inclined surfaces, *α*>1 was required inside the exponential function of Eq.(15) giving

|  |  |
| --- | --- |
|  | (16) |

where

|  |  |
| --- | --- |
|  | (17) |

Hence for impacts on a horizontal surface, *α*=1; this gives the same equation format as Mitchell et al. [15].

From Eq.(16), the time to peak force is given by

|  |  |
| --- | --- |
|  | (18) |

for which substitution of *t*p back into Eq. (16) gives the peak force

|  |  |
| --- | --- |
|  | (19) |

For application to non-spherical drops that impact at terminal velocity on both horizontal and inclined surfaces, experimental data from Yu and Hopkins [14] on horizontal plates is combined with experimental data in this paper on an inclined surface. The constants *C* and *τ* are determined by using regression analysis to give a relationship between the experimental data and highly-idealised geometrical parameters that describe the impact of an ellipsoidal drop. Note that the time-dependent force is not closely described by any of the idealised drop shape models (spherical, ellipsoidal, paraboloidal, cylindrical-hemispherical) [14], but consideration of an ellipsoidal drop shape is a useful starting point because at the drop velocities found in artificial (ISO 10140) and natural rain, the drops tend to be ellipsoidal for equivalent drop diameters between 2 and 5 mm. This can be seen in the measured and estimated [16] ellipsoidal axis ratios tabulated in Table 5 (NB Estimates of axis ratios for other drop velocities can be estimated by interpolating between these data.). Note that the ellipsoidal drop shape model in previous work [14] applied to impacts on horizontal surfaces at terminal velocity. For this reason, a new approach based on an ellipsoidal drop shape is developed; this maps the highly idealised geometrical parameters that are based on an ellipsoidal drop onto the experimental data. To account for inclined surfaces it is assumed that the peak force will occur when the cross-sectional area through the ellipsoidal shape that is formed by the surface reaches a maximum value, *S*max. This is illustrated in Fig. 6 where the plane formed by the inclined surface is shown (a) when touching the edge of the drop and (b) when it cuts through the ellipsoidal drop at the point where its internal cross-sectional area is at its maximum. It is assumed that the drop shape does not change over the distance, *l*max, between these two planes such that the time to peak force is *l*max/*v*d,n.

To extend the model to any drop diameter that occurs in natural rain, curve fitting is used to link the dimensionless parameter, *l*max/*D*, that is calculated for an ellipsoidal drop, to the dimensionless time to peak force from the experimental data, *t*p/(10-3*D*/*v*d,n). This is shown in Fig. 7(a), which gives

|  |  |
| --- | --- |
|  | (20) |

Similarly, curve fitting of the dimensionless parameter, *S*max/*D*2, calculated for an ellipsoidal drop makes a link to the dimensionless peak force from the experimental data, *f*p/(10-6*ρ*w*v*d,n2*D*2), as shown in Fig. 7(b), giving

|  |  |
| --- | --- |
|  | (21) |

**2.3 Calculation of input power**

For a plate that is excited by artificial or natural rainfall, it is the radiated sound power that is usually of most interest. This is directly proportional to the structure-borne sound power input; hence calculation of the difference in the structure-borne sound power input for different types of rainfall can be used to estimate the change in the radiated power.

To calculate the structure-borne sound power input from steady-state rainfall (artificial or natural) it is necessary to determine the number of drops per second, *N*, that fall upon the test element. For artificial rain at a known rainfall rate, *R*r, the number of drops per second is given by

|  |  |
| --- | --- |
|  | (22) |

and for natural rainfall defined by the Marshall-Palmer distribution, the number of drops per second per unit area for each drop diameter interval, δ*D*, is calculated using

|  |  |
| --- | --- |
|  | (23) |

The structure-borne sound power input, *W*in, can then be calculated using

|  |  |
| --- | --- |
|  | (24) |

where |*F*(*f*)| is the energy spectrum from the Fourier transform of the time-dependent force that has been summed into frequency bands (e.g. one-third octave bands), and the flow impedance of a drop is given by Petersson [13] as

|  |  |
| --- | --- |
|  | (25) |

(NB The drop velocity, *v*d, equals the terminal velocity, *v*T, in Eq.(25) when natural rainfall is considered.)

The driving-point impedance of the plate, *Z*dp, can be measured or predicted. Assuming an infinite plate, the driving-point impedance can be predicted using

|  |  |
| --- | --- |
|  | (26) |

where *ρ* is the plate material density, *c*L is the longitudinal wave speed of the plate and *h* is the plate thickness. Whilst the application of this infinite plate equation to many plate-like structures in buildings is well-established (e.g. see examples in [1]) there are few measurements indicating its application to roof glazing using IGUs or multilayer metal roofs where the mass-spring-mass resonance occurs in the frequency range of interest. Hence, it would be useful for future experimental work to assess its validity near the mass-spring-mass resonance.

The flow impedance tends to have negligible effect on the predicted power for common thicknesses of glass plate and metal sheet used in buildings and cars. Note that laboratory measurements with artificial rainfall usually provide excitation over a limited area (typically ≈1 m2) of a roof. Sound pressure measurements in the receiving room are then used to quantify the sound intensity level; hence when predicting the sound power radiated when an entire plate surface is exposed to natural rainfall, a correction must be made for the excitation area as described in [1].

**2.3 Calculation of plate velocity levels**

Experimental validation of the empirical models for the time-dependent force from artificial rain is carried out by measuring the spatial-average, mean-square velocity on the plate and comparing this with the predicted value that is determined from the predicted power input. The predicted spatial-average, mean-square velocity, <*v*2>, is calculated using

|  |  |
| --- | --- |
|  | (27) |

where *m* is the mass of the plate and the total loss factor, *η*, is given by

|  |  |
| --- | --- |
|  | (28) |

in which *f* is the band centre frequency and *T* is the measured structural reverberation time of the plate.

**3. Laboratory measurements**

**3.1 Force measurements with single drops on an inclined plate**

The test set-up and measurement procedures to determine the time-dependent force on a plate from single drops using wavelet measurements is described in detail in [14]. Doyle’s wavelet method [[[24]](#endnote-24)] and the sparse representation method are used to determine the impact force from the response signal on the plate. In the experiment, a matrix of transfer accelerances is determined by applying an impact force at the excitation position using a force hammer with a 3 mm diameter steel tip (Brüel & Kjær Type 8203). The acceleration at three sensing positions is then measured using accelerometers (Brüel & Kjær Type 4375) fixed with cyanoacrylate glue to the underside of the plate at randomly located positions. Ten hits are averaged to give each transfer accelerance value.

Measurements on a glass plate when horizontal (0°) were carried out along with measurements where the plate was inclined at an angle of 30°, 45°, or 60°. The drops were produced from a burette with a 4.5 mm diameter. Drop velocities were measured as described in [14] to be 7.03, 9.08 and 9.31 m/s (corresponding to drop heights of 3.65, 11.3 and 15.6 m) where the latter corresponds to terminal velocity. Before each measurement, the glass was cleaned and dried.

The 6 mm glass plate (1.53 × 1.28 m) was positioned inside a wooden frame and sealed with silicone sealant around the edges. Measurements of the structural reverberation time, *T*10, were used to determine an average value for the total loss factor of the glass plate; this was 0.022. The glass density was 2500 kg/m3 and the Young’s modulus was 74 GPa.

**3.2 Plate vibration measurements with artificial rain**

Experimental validation of the predicted power input from artificial rain falling on a plate is assessed using the spatial-average velocity level on a homogeneous, isotropic plate (e.g. glass). It can potentially be assessed using the radiated sound power, but this incurs additional uncertainty because the idealised boundary and baffle conditions used in prediction models for the radiation efficiency (e.g. see [1]) cannot always be arranged in the laboratory, and this can significantly affect the radiation below the critical frequency. For these experiments, the glass plate was the same as described in Section 3.1. The spatial-average velocity was measured using six accelerometers (Brüel & Kjær DeltaTron Type 4517) that were located randomly over the plate surface. The total loss factor was also determined from structural reverberation time measurements.

A rain box was built with the intention of producing single diameter raindrops at a steady rainfall rate. ISO 10140-5 describes a rain box that can produce artificial heavy rain with 5 mm diameter drops (median value) using 1 mm diameter holes in a 10 mm thick plate; however, a pre-test found that this resulted in 5.9 mm diameter drops. Therefore, an alternative was developed using nozzles inserted into the holes that gave 4.6 mm drops (NB Median and arithmetic average drop diameters were the same to one decimal place). To simulate heavy rain, ISO 10140-5 specifies a rainfall rate of 40±2 mm/h; however, the rainfall rate was measured during the actual measurement period (carried out on different days) and was found to be 30 mm/h for the 3.65 m drop height, and 24 mm/h for the 11.4 m drop height. These rainfall rates were in-between intense and heavy rain, but were too low to simulate heavy rain defined by ISO 10140-5. However, measurement of the rainfall rate allowed the power input to be calculated using the empirical models.

An engineering facility with teagle doors in the floor gave the headroom that was required for the drop heights – see Fig. 8. A drop height of 3.65 m gave a drop velocity of 7.09 m/s following the approach in ISO 10140-5 that requires ≈3.5 m to give 50% of drops with a drop velocity of 7±1 m/s. In addition, a drop height of 11.4m gave 9.09 m/s that represented terminal velocity (this was as close as possible to the 11.3 m height used for the single drop measurements described in Section 3.1).

**4. Results**

**4.1 Laboratory measurements**

**4.1.1 Assessment of the angle-corrected empirical and semi-empirical models for single drops**

This section assesses the validity of the angle-corrected empirical and semi-empirical models through comparison with the measured force from a single 4.5 mm drop impacting a dry horizontal plate (i.e. *θ*=0°), and the same dry plate inclined at *θ*={30°,45°,60°}. Three different drop velocities are considered: 7.03, 9.08, and 9.31 m/s where the latter corresponds to terminal velocity. For Fig. 9 the empirical models for the horizontal plate are described in Section 2.1.1 for the 7.03 and 9.08 m/s drop velocities and in Section 2.1.2 for terminal velocity. For the inclined plate these models are modified to give the angle-corrected empirical model as described in Section 2.2.1. For Fig. 10, the semi-empirical model described in Section 2.2.2 is used for both the horizontal and inclined plates.

From the time domain measurements (Figs. 9 and 10) it is seen that as the angle, *θ*, of the plate decreases from 60° to 0°, the peak force increases and the pulse width decreases. This can be attributed to the increase in the drop velocity component that is perpendicular to the plate surface as the angle decreases from 60° to 0°. Note that this was also observed in previous measurements [14] on a horizontal plate with different drop velocities.

For the empirical and angle-corrected empirical models in Fig. 9, it is seen that the lowest differences occur for the horizontal plate and that the difference in these models is within 2 dB up to 250, 1k and 800 Hz for drop velocities of 7.03, 9.08, and 9.31 m/s respectively. The largest differences occur between 1k and 5k Hz for the inclined plate at the two highest angles (45° and 60°) with the largest difference (9.4 dB at 3.15k Hz) occurring at a plate angle of 60° and terminal velocity. In practice, this increase in the difference above 1k Hz may not be problematic when calculating A-weighted levels for the radiated sound power because there is often a significant decrease in the radiated power above 2k Hz (e.g. for insulating glass units and multilayer roofs [1,2,7). However, the next step is to compare these differences with those from the angle-corrected semi-empirical model in Fig. 10. This shows differences for the horizontal and inclined plates that are within 2.5 dB up to 3.15k, 5k and 2.5k Hz for drop velocities of 7.03, 9.08, and 9.31 m/s respectively. The largest magnitude difference is 3 dB which occurs at a plate angle of 60° and terminal velocity. Hence, the angle-corrected semi-empirical model (Section 2.2.2) is reasonable for the range of drop velocities that occur in artificial and natural rainfall and typical inclination angles.

**4.1.2 Artificial rain**

Figure 11 allows comparison of the measured and predicted plate velocity of a 6 mm glass plate inclined at 30° under artificial rain excitation with a 3.65 m drop height, and with a drop height of 11.4 m to simulate a drop velocity close to terminal velocity. For both drop heights, the measurements below 1k Hz show closest agreement with the angle-corrected empirical or semi-empirical models assuming a dry surface rather than a 1 or 2 mm water layer. However, above 1k Hz they show closer agreement with the angle-corrected semi-empirical model that assumes a dry surface.

These experiments used rainfall rates of 30 and 24 mm/h that are lower than the 40 mm/h associated with heavy rain in ISO 10140-5 for which more surface water can be expected. The issue as to whether surface water should be considered when predicting the power input is not entirely resolved by the above finding because artificial raindrops from a rain box fall (approximately) at the same position and therefore there is a regular grid of drop impact positions where the jetting drops flow down the plate from the higher grid points down to the lower grid points. Natural rain will fall at random positions on a surface (rather than over a regular grid) and with heavy or torrential rainfall rates it is reasonable to assume that there will sometimes be a thin water layer flowing down an inclined plate. When assessing natural rain with rainfall rates ≥ 40 mm/h, the empirical model for a 1 or 2 mm surface water layer could be used to provide an upper estimate for the predicted plate velocity and radiated sound power in the low-frequency range.

With artificial rain used for measurements according to ISO 10140-5 the drops do not impact at terminal velocity; hence it is useful to assess whether the power input calculated using the angle-corrected empirical or semi-empirical model can be used to convert a laboratory measurement with drops that are close to terminal velocity, to a more realistic situation with terminal velocity drops. Figure 12 shows the difference between the two predicted power inputs for comparison with the difference in the measured mean-square plate velocity (which is directly proportional to the radiated sound power). Predictions using the angle-corrected empirical model are shown for a dry surface because it was established above that a dry surface was appropriate, but predictions are also shown for 1 and 2 mm water layers. This indicates that the difference between the models for dry and wet surfaces is ≤1.5dB in the low-frequency range (50 – 250 Hz), but is 4.5 dB at 5k Hz. Figure 12 shows that there is close agreement between the measured data and the following three predictions for a dry surface: (1) measured force from single drops reported in Section 4.1.1 for a plate inclined at 30°, (2) angle-corrected empirical model, and (3) angle-corrected semi-empirical model. However, above 2k Hz the angle-corrected semi-empirical model (Section 2.2.2) shows closer agreement with measurements than the angle-corrected empirical model (Sections 2.1.1 and 2.1.2 that are modified according to Section 2.2.1). Hence it is proposed that the angle-corrected semi-empirical model for a dry surface should be used to convert laboratory measurements with artificial rain that were determined with one drop velocity with the surface at one inclination angle, to a different drop velocity (such as terminal velocity) and/or the surface at a different inclination angle.

**4.2 Numerical simulation of artificial and natural rainfall**

The angle-corrected semi-empirical model has now been experimentally validated; hence, this model is used to run numerical simulations to compare the structure-borne sound power input into a dry plate that is inclined at different angles from 0° up to 60°. For artificial and natural rain, the rainfall rates for moderate, intense and heavy rain are defined as 4, 15, and 40 mm/h respectively. For artificial rain, the drop diameters for moderate, intense and heavy rain are defined as 1, 2 and 5 mm respectively. In this section the plate is assumed to be 6 mm glass (*ρ*=2500 kg/m3, *c*L=5200 m/s) and the driving-point mobility is calculated from Eq.(26) for an infinite plate.

For artificial rain in Fig. 13(a) it is evident that as the angle increases, the power input decreases. As the angle increases, there are also differences in the spectral shape between moderate, intense and heavy rain.

For natural rain in Fig. 13(b) the power input also decreases as the angle increases. With differences up to ≈9 dB between 0° and 60° it is clearly important to take measurements with artificial rain using the inclination that will be installed in the actual building. For all rainfall rates, the difference between the power input at 0° and 15° is <1 dB up to 1k Hz; hence for shallow angle roofs the exact angle is not critical. However, below 200 Hz the power input at 60° is ≈7 dB lower than at 30° for intense, heavy and moderate rain. For future work on roof elements and car windscreens it should be noted that at a relatively steep angle such as 60°, wind-driven rain with a significant horizontal velocity component could primarily determine the rain noise from natural rainfall.

For any plate thickness where *Z*dp >> *Z*f, the predicted power inputs from Fig. 13 can be used to convert (a) a laboratory measurement with one type of artificial rain to a different type of artificial rain, (b) a laboratory measurement with one type of artificial rain to natural rain with a specified rainfall rate, (c) a laboratory measurement on a roof element inclined at one angle to a different angle and (d) a field measurement using natural rain with a known rainfall rate to natural rain with a different rainfall rate. For the conversions that are of most practical interest, the conversion factors in one-third octave bands are shown in Fig. 14. As an example of how these are used, consider the curve corresponding to “Artificial Heavy to Natural Intense”, the conversion factor in decibels is added to the measured radiated sound power in decibels when using artificial heavy rainfall in the laboratory to give an estimate of natural intense rainfall. Some of the spectral shapes for these conversion factors are sufficiently invariant with frequency that it is reasonable to consider using a single-number conversion factor based on an arithmetic average of the differences between the two power inputs of interest (in decibels) for all one-third octave bands between 50 and 5k Hz. These conversion factors are given in Table 7. An indication of the robustness of these single-number values can be made by checking the maximum difference from the single-number value in any band between 50 and 5k Hz; the closer the difference is to 0 dB, the more reliable the single-number. For some conversions (e.g. artificial moderate to artificial intense) the conversion factor is sufficiently similar for all angles between 0° and 60° that a single arithmetic average of the tabulated values could be used as shown in the bottom row of Table 7.

**5. Conclusions**

Empirical models have been extended to predict the time-dependent force on both horizontal and inclined plates and provide predictions for the wide range of drop diameters that occur with natural rain. For inclined plates, two approaches were developed. The first approach uses the empirical model for a horizontal plate (dry or with surface water) and converts it to an inclined plate by estimating the drop velocity in the direction that is perpendicular to the plate surface. The second approach extends a semi-empirical model for dry, horizontal plates so that it applies to drops falling at terminal velocity on a dry, inclined plate. The experimental validation used 4.5 mm drops for plates inclined up to 60°, from which the results indicated that the second approach showed better agreement. Further validation using artificial rain measurements for rainfall rates between 24 and 30 mm/h indicated that this model is valid even though it assumes a dry surface. However, for heavy and torrential rain (i.e. rainfall rates higher than 40 mm/h), the first approach to modelling allows the option to include a 1 or 2 mm water layer on the surface. The validated second approach has been used to calculate conversion factors for (a) a laboratory measurement with one type of artificial rain to a different type of artificial rain, (b) a laboratory measurement with one type of artificial rain to natural rain with a specified rainfall rate, (c) a laboratory measurement on a roof element at one angle to a different angle, and (d) a field measurement using natural rain with a known rainfall rate to natural rain with a different rainfall rate.

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**References**

**Figures**



Figure 1. Comparison of the wavelet measurement, the empirical model from Yu and Hopkins, Petersson’s idealised models for the paraboloidal and cylindrical–hemispherical drop shapes and Mitchell et al’s model. Time-dependent forces are shown for (a) 2 mm drops and (b) 4.5 mm drops, with the difference between the wavelet measurement and the four different models in the frequency domain shown in (c).



Figure 2. Examples of the Marshall-Palmer distribution for three different rainfall rates.



Figure 3. Model for natural rain at terminal velocity: Determination of parameter *C*1 for a dry surface from measurements of 2 mm drops (blue line) and 4.5 mm drops (red line) using regression (open circles indicate the values corresponding to terminal velocity measurements).



Figure 4. Empirical model for natural rain at terminal velocity on a horizontal plate: (a) Dimensionless force applied by different drop diameters, (b) Energy Spectral Density (ESD). Measured data from [14] is shown on (a) and (b) for 2 and 4.5 mm drops on a dry glass plate.



Figure 5. Velocity components for a raindrop falling with drop velocity, *v*d, onto an inclined plate (NB In this sketch the drop shape is chosen to represent a 5 mm drop at terminal velocity).



Figure 6. Angle-corrected semi-empirical model for an impact on an inclined surface illustrating (a) the distance, *l*max, when the drop touches the surface and (b) the corresponding cross-sectional area, Smax.



Figure 7. Regression analysis: (a) linking the dimensionless parameter, *l*max/*D*, for an ellipsoidal drop to the dimensionless time to peak force from the experimental data, *t*p/(10-3*D*/*v*d,n), and (b) linking the dimensionless parameter, *S*max/*D*2, for an ellipsoidal drop to the dimensionless peak force from the experimental data, *f*p/(10-6*ρ*w*v*d,n2*D*2).



Figure 8. Laboratory set-up for experiments using artificial rain from a rain box.



Figure 9. Comparison of the force from measurements and the angle-corrected empirical models described in Sections 2.1.1, 2.1.2 and 2.2.1 for a single 4.5 mm drop impacting on a dry glass plate inclined at angles, *θ*={0°,30°,45°,60°} where 0° describes the horizontal plate. Results are shown for three different drop velocities: (a) 7.03 m/s, (b) 9.08 m/s, and (c) 9.31 m/s (terminal velocity). The first column shows the time-dependent zero-padded initial impact force, the second column shows the Energy Spectral Density (ESD) in narrow bands, the third column shows the difference between the measured ESD from wavelet deconvolution and the empirical models.



Figure 10. Comparison of the force from measurements and the angle-corrected semi-empirical model described in Section 2.2.2 for a single 4.5 mm drop impacting on a dry glass plate inclined at angles, *θ*={0°,30°,45°,60°} where 0° describes the horizontal plate. Results are shown at three different drop velocities: (a) 7.03 m/s, (b) 9.08 m/s, and (c) 9.31 m/s (terminal velocity). The first column shows the time-dependent zero-padded initial impact force, the second column shows the Energy Spectral Density (ESD) in narrow bands, the third column shows the difference between the measured ESD from wavelet deconvolution and the semi-empirical models.



Figure 11. Velocity of a 6 mm glass plate inclined at 30° when excited by artificial rainfall comprising 4.6 mm drops: Comparison of prediction using the angle-corrected empirical model and measurements for (a) drop velocity of 7.09 m/s (drop height of 3.65 m, rainfall rate of 30 mm/h), and (b) drop velocity of 9.09 m/s (drop height of 11.4 m, rainfall rate of 24 mm/h).



Figure 12. Difference between the power input applied by artificial rainfall on a glass plate inclined at 30° when excited by artificial rainfall (4.6 mm drops) at two different drop heights (the difference corresponds to the velocity at 11.4 m minus the velocity at 3.65 m) for comparison with the difference in the measured mean-square velocity (spatial average).



Figure 13. Power input from three different types of (a) artificial rainfall and (b) natural rainfall onto a dry glass plate when horizontal and inclined at angles up to 60°. All data are calculated using the angle-corrected semi-empirical model.



Figure 14. Conversion factors between the power input for different types of artificial and natural rainfall in one-third octave bands: (a) artificial moderate to artificial intense and artificial intense to artificial heavy, (b) artificial moderate to natural moderate and artificial intense to natural intense, (c) artificial heavy to natural moderate/intense/heavy, (d) natural moderate to natural intense and natural intense to natural heavy.

**Tables**

Table 1. Empirical formulae constants for 2 mm drops at drop velocities that are lower than terminal velocity on a horizontal plate (Values taken from [14] for 2 mm drops).

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Water layer depth, *d* (mm) | *aC* | *bC* | *aα* | *bα* | *aβ* | *bβ* |
| 0 (dry) | 0.5088 | –5.001 | 0.1748 | 1.3930 | –0.0727 | 1.3148 |
| 1 | 0.4728 | –4.7645 | 0.2003 | 0.5220 | 0.0270 | 0.9816 |
| 2 | 0.4402 | –4.5871 | 0.2266 | 0.1213 | 0.0584 | 0.9180 |

Table 2. Empirical formulae constants proposed for 5 mm drops at drop velocities that are lower than terminal velocity on a horizontal plate (Values taken from [14] for 4.5 mm drops).

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Water layer depth, *d* (mm) | *aC* | *bC* | *aα* | *bα* | *aβ* | *bβ* |
| 0 (dry) | 0.4616 | –3.1084 | 0.3391 | 0.2307 | 0.0381 | 1.1176 |
| 1 | 0.4227 | –2.9358 | 0.3672 | –0.7840 | 0.1314 | 0.5461 |
| 2 | 0.4153 | –2.9193 | 0.3703 | –0.9777 | 0.1392 | 0.4741 |

Table 3. Empirical formulae constants for 2 mm drops at terminal velocity on a horizontal plate (Values taken from [14] for 2 mm drops).

|  |  |  |  |
| --- | --- | --- | --- |
| Water layer depth, *d* (mm) | *C*A | *α*A | *β*A |
| 0 (dry) | 0.1389 | 2.5912 | 0.9867 |
| 1 | 0.1504 | 2.0231 | 1.1196 |
| 2 | 0.1553 | 1.6889 | 1.1136 |

Table 4. Empirical formulae constants proposed for 5 mm drops at terminal velocity on a horizontal plate (Values taken from [14] for 4.5 mm drops).

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Water layer depth, *d* (mm) | *C*A1 | *C*A2 | *α*A1 | *α*A2 | *β*A1 | *β*A2 |
| 0 (dry) | 2.7186 | 0 | 3.3367 | 0 | 1.5027 | 0 |
| 1 | 1.7168 | 1.5693 | 2.0703 | 2.8439 | 1.3129 | 0.4645 |
| 2 | 1.7673 | 1.2078 | 1.8683 | 2.8984 | 1.4361 | 0.509 |

Table 5. Parameters for the impact force of any drop diameter at terminal velocity on a horizontal plate.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Water layer depth,*d* (mm) | *C*a1 | *C*a2 | *C*b1 | *C*b2 | *C*b3 |  |  |  |
| 0 | 2.32E-07 | 8.49E-04 | 8.22E-07 | 2.30E-04 | 1.14E-01 | 0 | 0 | 0 |
| 1 | 2.16E-07 | 8.72E-04 | 3.53E-07 | 6.88E-04 | 2.25E-02 | 1.5693 | 2.8439 | 0.4645 |
| 2 | 1.83E-07 | 8.49E-04 | 3.74E-07 | 6.05E-04 | 4.40E-02 | 1.2078 | 2.8984 | 0.509 |

Table 6. Drop axis ratio. M indicates measured data and E indicates estimated from Beard et al. [16].

|  |  |
| --- | --- |
| Drop diameter (mm) | Drop velocity (m/s) |
| 2.57 | 2.69 | 3.77 | 5.18 | 6.50 | 6.73 | 8.2 | 9.3 |
| 2 | 1.00 (M) | - | - | - | 0.91 (E) | - | - | - |
| 4.5 | - | 0.98 (M) | 0.96 (M) | 0.95 (M) | - | 0.86 (M) | 0.79 (M) | 0.75 (E) |

Table 7. Conversion factors between the power input for different types of artificial and natural rainfall. These are calculated in terms of a single-number value which is the arithmetic average of the differences between two types of rainfall in one-third octave bands between 50 and 5k Hz. The value in brackets indicates the maximum difference from this single-number in any of the one-third octave bands.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Inclination angle of the plate | Artificial Moderate to Artificial Intense (dB) | Artificial Intense to Artificial Heavy (dB) | Artificial Moderate to Natural Moderate (dB) | Artificial Intense to Natural Intense (dB) | Artificial Heavy to Natural Moderate(dB) | Artificial Heavy to Natural Intense(dB) | Artificial Heavyto Natural Heavy (dB) | Natural Moderate toNatural Intense (dB) | Natural Intenseto Natural Heavy (dB) |
| 0° | 20.9(0.8) | 20.2(1.5) | 21.8(5.9) | 10.6(5.8) | -19.3(4.8) | -9.6(4.7) | -3.1(4.6) | 9.7(0.6) | 6.5(0.3) |
| 15° | 20.6(1.4) | 20.3(0.4) | 21.9(5.1) | 10.9(3.8) | -22.1(4.4) | -12.5(4.3) | -2.9(4.3) | 9.6(0.2) | 6.5(0.1) |
| 30° | 21.3(0.7) | 19.3(0.2) | 22.2(3.3) | 10.2(3.6) | -18.5(3.7) | -9.2(3.7) | -2.9(3.6) | 9.3(0.2) | 6.3(0.2) |
| 45° | 20.7(0.6) | 19.2(3.3) | 22.1(3.0) | 10.5(1.6) | -17.9(5.0) | -8.7(4.5) | -2.6(4.2) | 9.2(0.7) | 6.1(0.6) |
| 60° | 20.6(0.6) | 18.4(6.4) | 22.2(3.9) | 10.6(1.9) | -16.8(7.9) | -7.8(6.8) | -1.8(6.2) | 9.0(1.5) | 6.0(1.0) |
| Average(0° to 60°) | 20.8 | 19.5 | 22.0 | 10.6 | -18.9 | -9.6 | -2.7 | 9.4 | 6.3 |

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