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Short note

Tachikawa number: A proposal

J.D. Holmes[a,*], C.J. Baker[b], Y. Tamura[c]

[a]JDH Consulting, P.O. Box 269, Mentone, Victoria 3194, Australia
[b]Department of Civil Engineering, University of Birmingham, Edgbaston, Birmingham B15 2TT, England, UK
[c]Department of Architecture, Tokyo Polytechnic University, 1583, Iiyama, Atsugi, Kanagawa 243-0297, Japan

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Abstract

This paper describes the studies of windborne debris by Masao Tachikawa and shows that a parameter defined by him, representing the ratio of aerodynamic to gravity forces, is the main non-dimensional parameter determining the trajectories of debris items of all types. A case for naming this parameter as the "Tachikawa Number" is made.

Keywords: Debris; Tachikawa parameter

1. Introduction

Professor Masao Tachikawa (January 14, 1929–March 20, 2001) was a pioneer in the study of windborne debris who studied experimentally and numerically the trajectories of generic debris types, at Kagoshima University in Japan in the 1980s [1,2]. Amongst his significant insights was the recognition of the importance of the non-dimensional ratio of aerodynamic forces to gravity forces to the flights of flat plates, referring to this ratio as a parameter "K" in his 1983 paper "Trajectories of flat plates in uniform flow with applications to wind-generated missiles" [1], published in this journal (this paper was also presented at the Sixth International Conference on Wind Engineering in March 1983).

This paper describes the studies by Masao Tachikawa and shows that the parameter defined by him is the main non-dimensional parameter determining the trajectories of

*Corresponding author. Tel.: +61395845885; fax: +61395853815.
E-mail address: jdholmes@bigpond.net.au (J.D. Holmes).

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debris items of *all* types, and appears irrespective of which form of non-dimensionalisation of the equations of motion is used.

2. The life and career of professor M. Tachikawa

Professor Masao Tachikawa (Fig. 1) received his Bachelor's degree from The University of Tokyo, Japan, in 1952. He was awarded Doctor of Engineering in 1971 from the same university for the dissertation entitled "Fundamental studies on the features of fluctuating wind pressures on buildings".

He first worked for the Nippon Oil Corporation, Japan, as a structural engineer for 7 years from 1952 to 1959. He joined Kagoshima University (KU), Japan, in 1959, and started his study of wind engineering. He said that he started wind engineering simply because Kagoshima was a typical place in Japan subject to typhoon attack. He was a Professor at KU for 19 years from 1975 to 1994, and was a Professor Emeritus later. He served as Dean of the Faculty of Engineering, KU, from 1988 to 1991. After retirement from KU, he was the President of Sendai Polytechnic College from 1994 to 1997.

Masao Tachikawa achieved excellence in the field of wind engineering, and in 1993 he received an Award of the Japan Association for Wind Engineering (JAWE) in recognition of his outstanding and innovative contributions.

His first paper in English was "Wind pressure measurements on bluff bodies in natural winds." This paper appeared in the Proceedings of US-Japan Research Seminar WIND LOADS ON STRUCTURES, October 1970, University of Hawaii. He presented the results of measurements of fluctuating wind pressures on prisms with a square and a rectangular section model mounted on the rooftop of a four-storey building. The wind pressures were measured by six pressure transducers and 20–30 U-tube manometers. The transducers were manufactured by him in 1965, and it was a pioneering work in wind pressure measurements under field conditions. He used intermediate-size models to compensate for various difficulties in full-scale measurements of fluctuating pressures acting on buildings and different features of wind characteristics in wind tunnels.

Fig. 1. Professor Masao Tachikawa (1929–2001).

He started his study on windborne debris in 1981, and published eight papers in Japanese and two famous papers in English on this subject.

Masao Tachikawa provided excellent leadership and made significant contributions in the fields of wind engineering and structural engineering, and had the honour of serving in important roles in Japanese society such as a councilor of the Architectural Institute of Japan, a member of the Liaison Conference on Disaster Engineering of the Science Council of Japan, a member of the Executive Board of the Japan Association for Wind Engineering (JAWE), a member of the Review Board of Licensed Architects in Kagoshima, and so on.

Masao Tachikawa passed away on March 20, 2001. One year before his death, he gave a Keynote Lecture entitled "Typhoon damage to buildings and structures" at the "JAWE Typhoon Forum" held in Kagoshima in 2000. His lecture was very impressive and informative, showing various examples of wind-induced damage to buildings and structures, and emphasised the importance of considering the damaging impacts of windborne debris in building design.

3. Equations of motion of windborne debris

The equations of motion of a general debris object (e.g. a flat plate) moving in a vertical plane were stated in the 1983 paper of Professor Tachikawa [1]:

$$\frac{\mathrm{d}^2x}{\mathrm{d}t^2} = \frac{\rho_a(C_D \cos\beta - C_L \sin\beta)[(U-u_m)^2 + v_m^2]}{2\rho_m h}, \tag{1}$$

$$\frac{\mathrm{d}^2z}{\mathrm{d}t^2} = \frac{\rho_a(C_D \sin\beta + C_L \cos\beta)[(U-u_m)^2 + v_m^2]}{2\rho_m h} - g, \tag{2}$$

$$\frac{\mathrm{d}^2\theta}{\mathrm{d}t^2} = \frac{\rho_a C_M A\ell[(U-u_m)^2 + v_m^2]}{2I}, \tag{3}$$

where ρ_a is the density of air, ρ_m is the density of the plate material, U is the wind speed, u_m is the horizontal velocity of the plate, v_m is the vertical velocity of the plate, h is the thickness of the plate, ℓ is the side dimension of the plate, A is the plan area (ℓ^2), I is the mass moment of inertia, C_D, C_L and C_M are the drag, lift and moment coefficients, x is the horizontal distance traveled, z is the vertical distance traveled, θ is the angle of rotation, β is the effective angle of attack of the relative wind to the horizontal, g is the acceleration due to gravity and t is time.

In the same paper, he proposed the following non-dimensional forms of the variables:

$$\bar{x} = \left(\frac{xg}{U^2}\right),\quad \bar{z} = \left(\frac{zg}{U^2}\right),\quad \bar{t} = \left(\frac{tg}{U}\right),\quad \bar{u} = \left(\frac{u_m}{U}\right),\quad \bar{v} = \left(\frac{v_m}{U}\right).$$

Then he re-formulated the equations of motion, (1), (2), (3), using the non-dimensional forms:

$$\frac{\mathrm{d}^2\bar{x}}{\mathrm{d}\bar{t}^2} = K(C_D \cos\beta - C_L \sin\beta)[(1-\bar{u})^2 + \bar{v}^2], \tag{4}$$

$$\frac{d^2\bar{z}}{d\bar{t}^2} = K(C_D \sin\beta + C_L \cos\beta)[(1-\bar{u})^2 + \bar{v}^2] - 1, \tag{5}$$

$$\frac{d^2\theta}{d\bar{t}^2} = \Delta K \, Fr_\ell^2 C_M[(1-\bar{u})^2 + \bar{v}^2], \tag{6}$$

where the following non-dimensional parameters are introduced:

$$K = \frac{\rho_a U^2 \ell^2}{2mg}, \tag{7}$$

where m is the mass of the plate $= \rho_m \ell^2 h$,

$$Fr_\ell = \frac{U}{\sqrt{g\ell}} \quad \text{(a Froude Number)}, \tag{8}$$

$$\Delta = \frac{m\ell^2}{I}. \tag{9}$$

(The notation used by Professor M. Tachikawa was slightly different to that used above.)

Note that the parameter K, as defined in Eq. (7), appears in all three Eqs. (4)–(6).

Baker [3] has proposed an alternative non-dimensional scheme for the equations of motion of windborne debris.

The non-dimensional parameters given by Baker are

$$\begin{aligned}
\bar{u} &= u/U,\\
\bar{v} &= v/U,\\
\bar{x} &= (x/\ell)(0.5\rho_a Al/m) = (x/\ell)\Phi,\\
\bar{y} &= (y/\ell)(0.5\rho_a Al/m) = (y/\ell)\Phi,\\
\bar{\theta} &= \theta(0.5\rho_a A\ell/m) = \theta\Phi,\\
\bar{t} &= (tU/\ell)(0.5\rho_a A\ell/m) = (tU/\ell)\Phi,\\
\Phi &= 0.5\rho_a A\ell/m.
\end{aligned}$$

The non-dimensional form of the equations then become

$$\frac{d^2\bar{x}}{d\bar{t}^2} = (C_D \cos\beta - C_L \sin\beta)[(1-\bar{u})^2 + \bar{v}^2], \tag{10}$$

$$\frac{d^2\bar{z}}{d\bar{t}^2} = (C_D \sin\beta + C_L \cos\beta)[(1-\bar{u})^2 + \bar{v}^2] - \left(\frac{1}{K}\right), \tag{11}$$

$$\frac{d^2\bar{\theta}}{d\bar{t}^2} = \Delta(C_M)((1-\bar{u})^2 + (\bar{v})^2). \tag{12}$$

The parameter K appears in this version of the equation of vertical acceleration in a reciprocal form, although it does not appear in the equations of horizontal and angular acceleration.

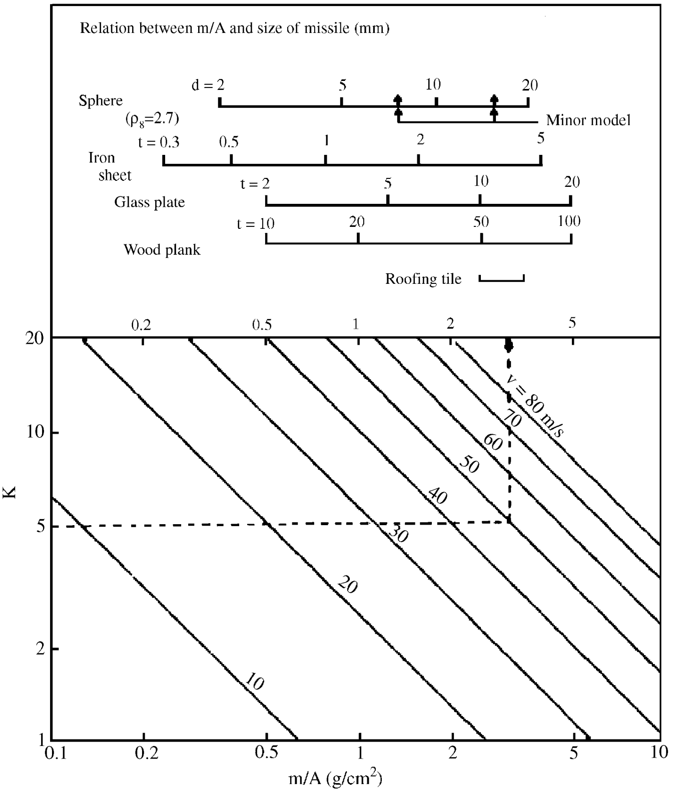

Fig. 2. Variation of the Tachikawa parameter, K, as a function of missile properties and windspeed (from Ref. [4]).

4. The parameter, K

The parameter K, as defined by Tachikawa, is a function of the windspeed, U, and the geometry and mass density of the windborne object. It is effectively the ratio of aerodynamic forces to gravitational forces. Thus, light (low mass) bodies with large surface areas have high values of K, and are prone to fly further and faster. K appears in both non-dimensional forms of the equations of motion, as discussed in the previous section.

In Ref. [4], Professor Tachikawa gave a chart showing values of K for various materials as a function of their densities, their characteristic dimensions, ℓ, and the wind speed, U. This is reproduced in Fig. 2. Thus a roof tile, at a wind speed of 50 m/s, has a value of K of about 5.

Lin et al. [5] showed, by analysis of a large number of experimental trials, that the horizontal trajectories of plates are strongly dependent on K (the vertical trajectories are more dependent on the initial angle of attack). Holmes et al. [6] show non-dimensional solutions of the equations of motion for square flat plates using the non-dimensional variables proposed by Tachikawa. Again, these show strong dependence on K of the horizontal trajectories. There is a much weaker dependence on the Froude Number, Fr_ℓ.

5. Conclusion and recommendation

In the previous sections, the pioneering work carried out by Professor Masao Tachikawa on the mechanics and aerodynamics of windborne debris in the 1980s has been discussed. The non-dimensional parameter, K, defined in 1988 by Professor Tachikawa (see also Eq. (7)), representing the ratio of aerodynamic forces (actually the product of the dynamic pressure and a reference area) to gravity forces acting on a windborne missile, is the main parameter determining the trajectories of debris objects of all types. For a given missile type (i.e. compact, plate/sheet, or rod type), a higher value of K indicates a greater propensity of a missile to "fly" further and faster under wind action.

Previously, in this journal, proposals have been made to describe the mass-damping parameter as the "Scruton Number" [7], and the ratio of building height to roughness length as the "Jensen Number" [8]. The former is a measure of the tendency of a structure to vortex-induced vibration and galloping, and the latter is a scaling requirement for model testing of buildings in atmospheric boundary-layer simulations. These names have been widely, if not universally, accepted in wind engineering. Consistent with those previous proposals we suggest that the Tachikawa parameter, as defined by Eq. (7), be known as the "Tachikawa Number", and encourage its usage in wind engineering, as a recognition of Masao Tachikawa's pioneering work in the study of the trajectories of windborne debris.

Acknowledgements

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Appendix A. Listing of papers written by Professor M. Tachikawa on windborne debris

M. Tachikawa, Aerodynamic characteristic and trajectories of flat plates in uniform flow, *Proceedings of the 6th National Symposium on Wind Engineering*, (1980), 231–238 (in Japanese with an English summary).

M. Tachikawa and M. Fukuyama, Trajectories and velocities of typhoon-generated missiles, Part 1, Aerodynamic characteristics of flat plates and equations of motion, *Transactions of Architectural Institute of Japan*, 302 (1981), 1–11 (in Japanese with an English synopsis).

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M. Tachikawa, Trajectories and velocities of typhoon-generated missiles, Part 5, A method for estimating the dispersion range of wind-borne missile, *Journal of Structural and Construction Engineering, Transactions of Architectural Institute of Japan*, 363 (1986), 42–49 (in Japanese with an English synopsis).

M. Tachikawa, Flying roofs, Tales on Winds, Part II, Gihodo-Shuppan, (1986), 102–107 (in Japanese).

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Note: papers written in English are shown in **bold**.

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