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Proposed approach for determination of tributary areas for scattered pressure taps

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Abstract. In wind load calculations based on pressure measurements, the concept of 'tributary area' is usually used. The literature has less guidance for a systematic computational methodology for calculating tributary areas, in general, and for scattered pressure taps, in particular. To the best of the author's knowledge, there is no generic mathematical equation that helps calculate the tributary areas for irregular pressure taps. Traditionally, the drawing of tributary boundaries for scattered and intensively distributed taps may not be feasible (a time and resource consuming task). To alleviate this problem, this paper presents a proposed numerical approach for tributary area calculations on rectangular surfaces. The approach makes use of the available coordinates of the pressure taps and the dimensions of the surface. The proposed technique is illustrated by two application examples: first, quasi-regularly distributed pressure taps, and second, taps that have scattered distribution on a rectangular surface. The accuracy and the efficacy of the approach are assessed, and a comparison with a traditional method is presented.

Keywords: tributary area; pressure taps; data interpolation; three-dimensional mesh; delaunay triangulation; MATLAB

1. Introduction

In experimental wind engineering, pressure taps are commonly used for wind pressure measurements (Jeong *et al*. 2000, Endo *et al*. 2006, Uematsu *et al.* 2008, Lam and Li 2009, Liu *et al.* 2009, Aly et *al.* 2011, Kim *et al*. 2011). Wind load estimation on tall buildings, as well as large civil engineering structures and their components, may require the use of intensive pressure taps distributed on the outer surfaces of wind-tunnel test models (Simiu *et al*. 2008, Aly 2009, Aly *et al.* 2011, Rosa *et al*. 2012). In wind load calculations for cladding and other structures, the tributary area may be defined as the area surrounding to a pressure tap where the pressure is assumed to be equal. The concept is also used in other areas of civil engineering as the area directly supported by the structural member between contiguous supports (Ludwig Buildings 2006). The concept of tributary areas is very useful when computing the loading applied to load-carrying elements.

The literature has less guidance for a systematic computational methodology for calculating tributary areas for pressure taps. To the best of the author's knowledge, there is no generic mathematical equation that can calculate the tributary areas for scattered pressure taps. The

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traditional way is to imagine lines at the barriers of the tributary areas (these lines are designated half a distance between each two adjacent taps) and the areas for each tap be calculated separately (Main and Fritz 2006, Datin and Prevatt 2007). However, for scattered and intensively distributed taps, the calculation of the tributary areas becomes complex and a time-consuming task. Although AutoCAD software (Omura 2009) can help provide an estimate of an area with defined geometry, the drawing of the tributary boundaries for intensive and irregular taps can be unfeasible (a time and resource consuming process). In the current study, a proposed technique for tributary area's calculation for pressure taps distributed on rectangular surfaces is presented. The approach makes use of the available coordinates of the pressure taps and the dimensions of the surface. The accuracy and the efficacy of the proposed method are assessed via application examples.

2. Methodology

The proposed technique makes use of the outer dimensions of a certain rectangular surface bounding a group of pressure taps with a given coordinates to estimate the tributary areas. The approach is illustrated in Fig. 1. First, a grid of points is generated on the predetermined rectangular surface (see Fig. 2) and defined in the two lateral directions. In the X-direction, along the width of the surface (X), the average distance between any two arbitrary taps is obtained (dx), and the distance between any two successive points on the grid is assumed to be dx/N. N is a grid-refinement integer number which can be adapted to improve the accuracy of the estimated tributary areas. In the Y-direction, along the length of the surface (Y), the mean distance between any two taps, dy, is used to define the distance between any two consecutive points on the grid as dy/N.

The grid points can be generated within any computer programming language. After the grid points are generated, a wrapper function can be created allowing data types to be passed and returned, which can be used to evaluate functions of two variables and three-dimensional mesh/surface plots (surface function). By assuming a unit pressure at a certain i^{th} tap while all the other taps are considered to have zero pressure values, one can estimate the nearest grid points to this particular pressure tap. An interpolation function, with natural neighbor interpolants, needs to be created for this task. This performs a Delaunay triangulation of the data, which involves creating a mesh of triangles from the data chosen in such a way that the unique circle drawn through the three points of any triangle will enclose no other points (Cheng and Poon 2006, de Berg *et al.* 2008). For instance, a subroutine which creates an interpolant (with the 'nearest' technique method for data interpolation) that fits a surface of the form ZI = F(XI,YI) to the scattered data in (x, y and z); x and y are vectors of size n, where n is the number of pressure taps. The column vector z defines the pressure values at x and y (tap location), where the length of z equals n. By repeating the last step (assuming a unit pressure at a second tap while all the other taps have zero pressure values) for all the pressure taps, one can find the number of the grid points (N_i) on the tributary area of a particular pressure tap (i^{th} pressure tap, i = 1, 2, …n). The ratio of this number to the total number of the grid points (N_t) is approximately equal to the ratio of the tributary area of the i^{th} pressure tap to the total area of the rectangular surface (X × Y), on which the pressure taps are distributed. The tributary area A_i of any arbitrary pressure tap can be computed as follows

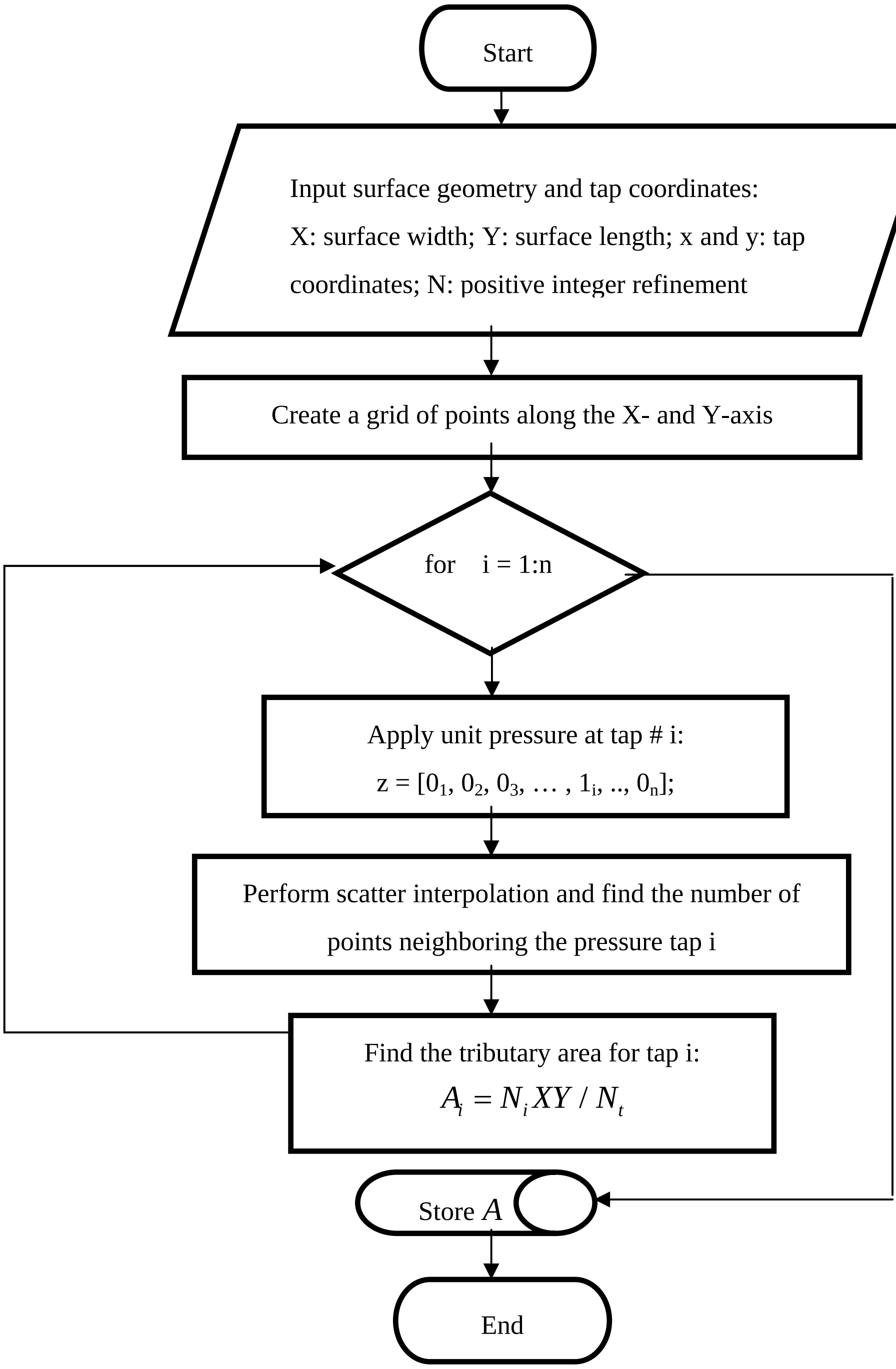


Fig. 1 Flow chart of the proposed approach for determination of tributary areas for scattered pressure taps on rectangular surfaces

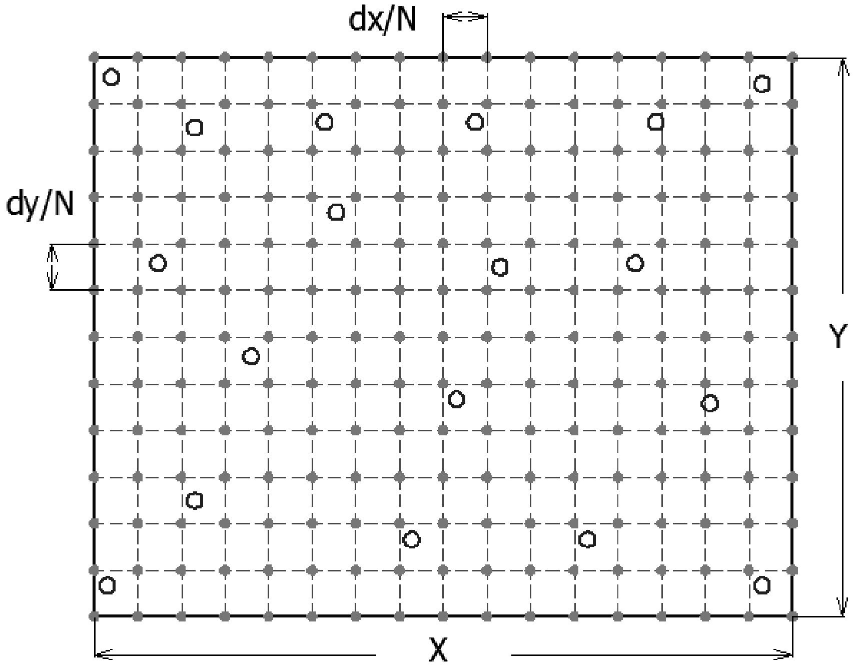


Fig. 2 Generated grid for the determination of the tributary areas for scattered pressure taps

$$A_i = \frac{N_i XY}{N_t}. \tag{1}$$

3. Application examples

To assess the accuracy and the efficacy of the proposed method, two explanation examples are considered: pressure taps distributed quasi-regularly and randomly (scattered) on rectangular surfaces. A personal portable computer that has an Intel® Core™ i5 CPU, installed memory (RAM) of 4.0 GB and running Ubuntu 64-bit operating system was used. The software used is MATLAB version 7.12, release R2011a (http://www.mathworks.com/, 2012).

3.1. Quasi-regularly distributed taps

Fig. 3 shows an example of a quasi-regularly distributed taps on a rectangular surface, the tap coordinates are listed in Table 1. First, the tributary areas were calculated (actual tributary areas) by gridding the surface to smaller rectangular shapes where the tributary barriers are half distance between adjacent taps. The proposed technique is then applied by making use of the outer dimensions of the rectangular surface on which the taps are distributed (6.4 m × 4 m). By using the proposed technique and running the simulations, one can get approximate values of the tributary areas. The percentage error in the calculations can be defined as

$$E_i\,(\%) = \frac{\left|A_{est,i} - A_{act,i}\right|}{A_{act,i}} \times 100 \tag{2}$$

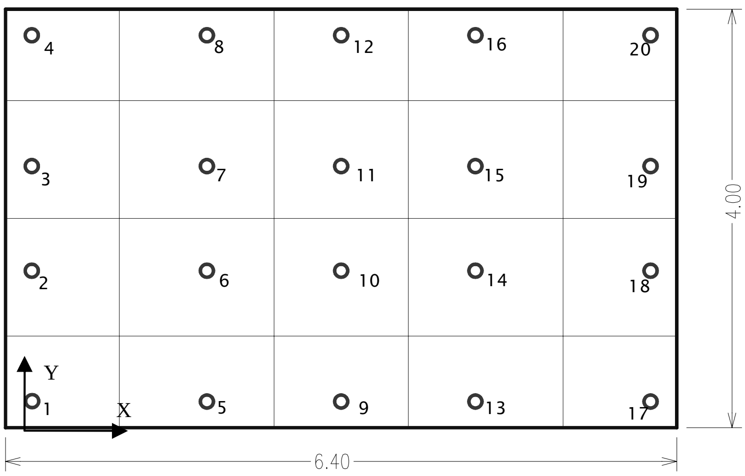


Fig. 3 Tributary areas for a quasi-regular tap layout with the coordinate system. Circles designate tap locations; thin lines represent tributary barriers; dimensions are in m

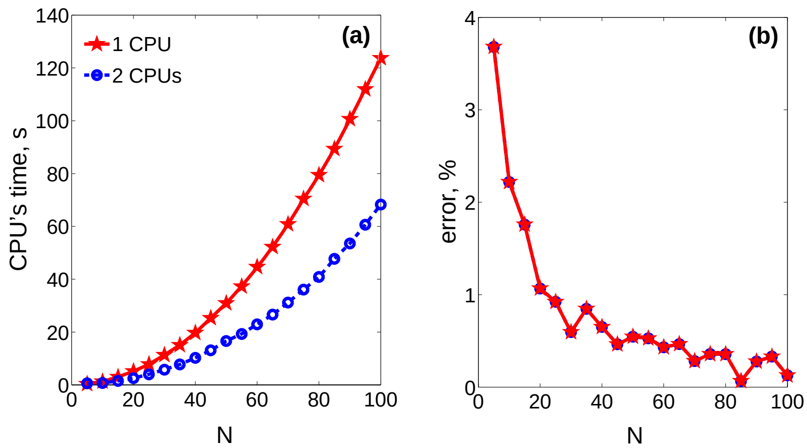


Fig. 4 Computation time and accuracy of tributary area calculations for quasi-regular tap layout (Fig. 3) as a function of the grid-refinement number *N*: (a) CPU time and (b) percentage of computation error

Table 1 Tap coordinates and geometrically calculated tributary areas (using AutoCAD software) for a regular tap layout

Tap number	X (m)	Y (m)	Area (m^2)
1	0.25	0.25	0.95
2	0.25	1.5	1.22
3	0.25	2.5	1.22
4	0.25	3.75	0.95
5	1.92	0.25	1.29
6	1.92	1.5	1.66
7	1.92	2.5	1.66
8	1.92	3.75	1.29
9	3.2	0.25	1.12
10	3.2	1.5	1.44
11	3.2	2.5	1.44
12	3.2	3.75	1.12
13	4.48	0.25	1.29
14	4.48	1.5	1.66
15	4.48	2.5	1.66
16	4.48	3.75	1.29
17	6.15	0.25	0.95
18	6.15	1.5	1.22
19	6.15	2.5	1.22
20	6.15	3.75	0.95

where E_i is the computation error in the calculation of the tributary area of the i^{th} pressure tap, $A_{est,i}$ is the estimated i^{th} tributary area (numerically computed using the proposed approach) on a given surface, and $A_{act,i}$ is the actual tributary area calculated using the AutoCAD software (CAD-based method). By increasing the grid-refinement number N, the error is reduced as shown in Fig. 4(b).

However, the time required for the computation (computational CPU time), which depends on the available computational resource as well as the number of taps and the surface size, is increased by increasing the number N. The figure shows that the computation time can be as short as a few seconds, while achieving reasonable accuracy (error less than 1%).

3.2. Randomly distributed taps

Fig. 5 shows an example of randomly distributed (scattered) taps on a rectangular surface. Even if this is an illustration of the procedure, it represents a practical situation where pressure taps are distributed over the surface of a paver located close to roof's corner. A similar tap layout was used in Aly *et al*. (2012). The tap coordinates are listed in Table 2. The tributary areas were calculated by dividing the surface into smaller irregular shapes where the tributary barriers are half a distance between any two adjacent taps. The figure shows that the random distribution of taps makes it complex for graphically computing the tributary areas. On the other hand, the proposed technique allows doing this process in a computational time of a few seconds with relatively acceptable accuracy. Fig. 6 shows the grid points close to tap number 5 of Fig. 5. At these points unit pressure values are assumed. The computation is achieved using a MATLAB function. The proposed function permits computing the tributary areas in a vector (AreaT) for pressure taps, with given coordinates x and y, on a rectangular surface with dimensions X (width) and Y (length). The error can be less than 1%, as shown in Fig 7 (b). The time required for the computation is dependent on the grid-refinement number *N* as well as the computational resources (number of CPU units). Figs. 4 and 7 show that when *N* is 5 the error is less than 5%. By increasing the number *N*, the error is reduced. However, the time required for the computation (computational CPU time) is increased by increasing the grid-refinement number *N*. In addition, this application example shows the feasibility of the proposed computation approach over the traditional CAD-based method.

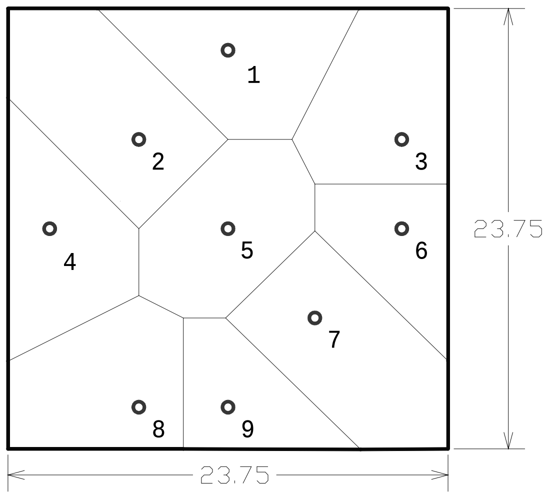


Fig. 5 Tributary areas for irregular tap layout (scatter distribution) with the coordinate system. Circles designate tap locations; thin lines represent tributary barriers; dimensions are in m

Table 2 Tap coordinates and geometrically calculated tributary areas (using AutoCAD software) for random tap layout (scatter distribution of taps)

Tap number	X (m)	Y (m)	Area (m^2)
1	11.88	21.50	62.12
2	7.06	16.69	79.56
3	21.25	16.69	65.46
4	2.25	11.88	62.90
5	11.88	11.88	65.64
6	21.25	11.88	43.34
7	16.56	7.06	79.06
8	7.06	2.25	64.35

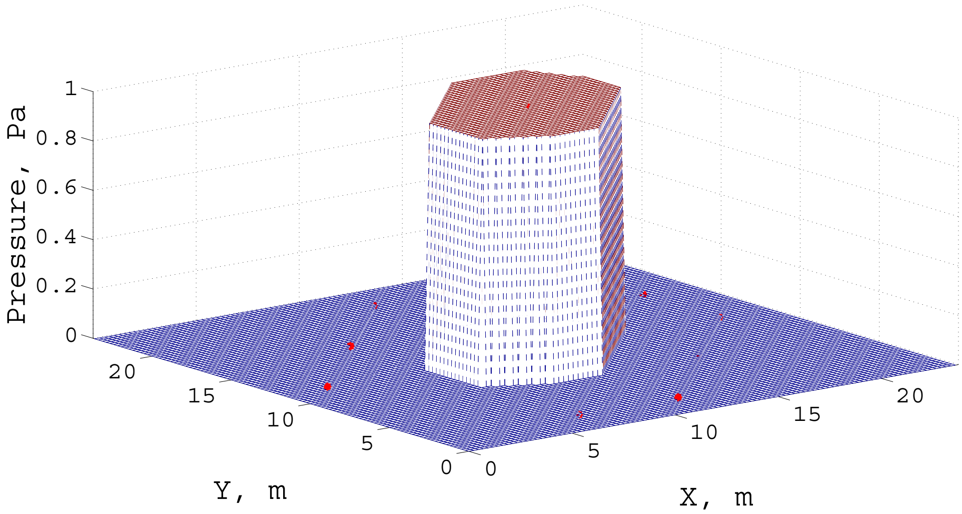


Fig. 6 An illustrative example of numerically calculating a tributary area at tap number 5 of Fig. 5

3.3. Comments and discussion

The current paper focuses on the calculations of tributary areas for pressure taps distributed on rectangular surfaces. In such case, to the best of the author's knowledge, no experimental procedures are required. However, the calculations of the tributary areas for structural loads distributed over columns, which is not the focus of the current paper, require cautions and the experimental verifications could be necessary.

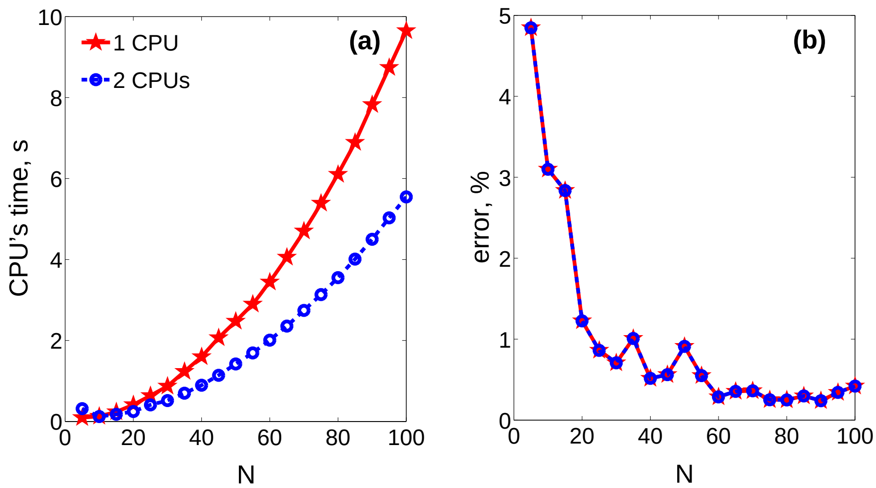
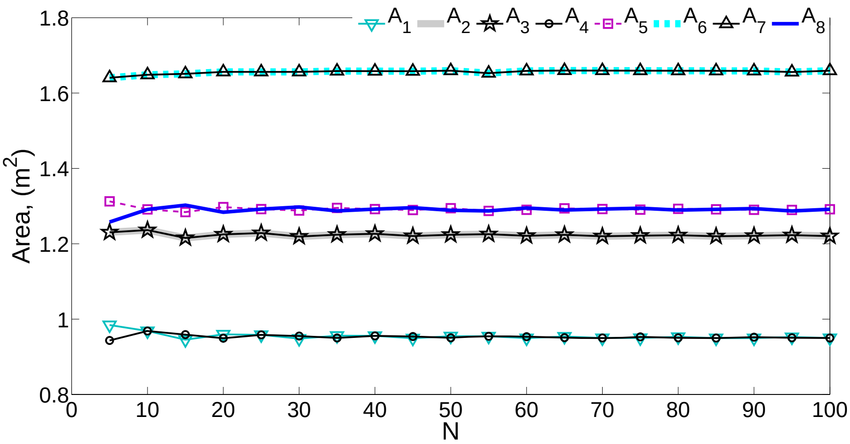
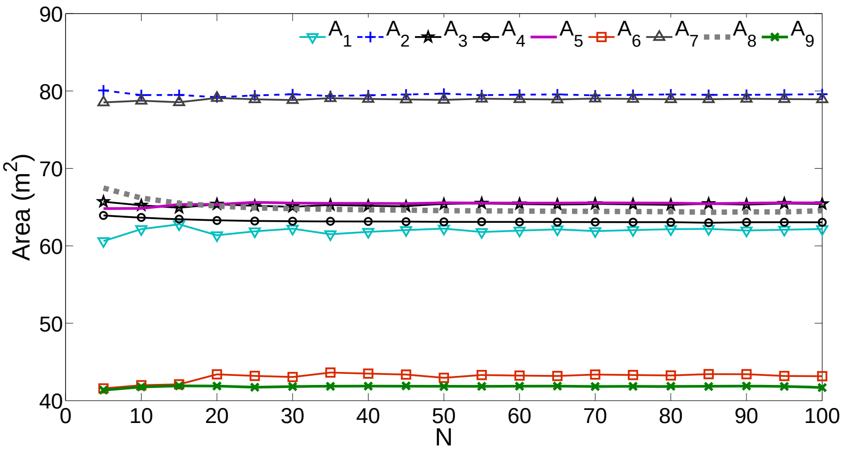


Fig. 7 Computation time and accuracy of tributary area calculations for scattered taps (Fig. 5) as a function of the grid-refinement number *N*: (a) CPU time and (b) percentage of computation error

Practically, the approach proposed in the current paper is useful when the tributary areas are not unknown. In such case, the confidence in the calculated areas is an important issue. To avoid doubt about the accuracy and to allow for confidence in the obtained values, one may plot the calculated areas versus the grid-refinement number *N*. By increasing the number *N*, as shown in the two applications examples, the error was reduced (see Figs. 4 and 7). At the same time, by increasing the number *N*, the trend of calculated tributary areas tends to be flat, as shown in Fig. 8. Once a satisfactory flat trend of the calculated areas is achieved, no more trials with the grid-refinement number *N* are needed. It is worth noting that once the calculated areas' trend is almost flat (horizontal line), for instance after *N* equals to 40 (see Fig. 8), the corresponding error obtained in Figs. 4 and 7 is relatively small (less than 1%).



(a) Tributary area calculations for quasi-regular tap layout (Fig. 3)



(b) Tributary area calculations for scattered taps (Fig. 5)

Fig. 8 Tributary areas' values as a function of the grid-refinement number *N*

It is important to mention that the proposed approach is basically advantageous when there are pressure taps with scattered distribution. However, it is also useful for other types of regular and irregular distributions. The calculations of the tributary areas in the current study were dominantly intended for pressure taps. The need to know how many pressure taps to use and where they should be put is always the choice of an aerodynamicist, which is usually governed by the location of the surface, its dimensions and the availability of pressure transducers as well as their size. For instance, recently hundreds of small-size pressure transducers can be used to cover the outer surfaces of tall buildings modeled for wind-tunnel experiments (see Aly 2009, Aly *et al*. 2011, Rosa *et al*. 2012).

Broadly speaking, the proposed approach might be useful for an approximate evaluation of the tributary areas for structural loads distributed over columns with hinges and simple supports. For other types of supports, caution is needed as the contribution of moments (mostly for frame-type structures and fixed supports) may require complex analysis. In such case, combined numerical/experimental investigations might be a requisite. However, the definition of error (tributary areas for the estimations of loads in columns and structural members) should refer to overall experimental accuracy. To do this, it would require comparing the method with a reference case for which the overall structural load effect of interest has been determined independently, e.g., by direct measurement of the load effect via strain gauges or displacement transducers.

4. Conclusions

In the literature, there is less guidance for a systematic computational methodology for calculating tributary areas for scattered pressure taps. Although AutoCAD software can help provide an estimate of an area with defined geometry, the drawing of the tributary boundaries for randomly and intensively distributed (scatter distribution) taps can be unfeasible (a time and resource consuming process). The current study presents a simple, yet accurate, method useful for the computation of the tributary areas of pressure taps distributed on rectangular surfaces. The proposed technique uses the coordinates of the pressure taps and the dimensions of the surface as well as a data interpolation method for the computation of the tributary areas. The technique is illustrated using two application examples that cover quasi-regular and random (scattered) tap layouts. Depending on the available computational resources, the required time can be as short as few seconds. The accuracy and the effectiveness of the approach are investigated numerically. By adjusting a predetermined grid-refinement integer number N, the computation accuracy can be adopted. However, the time required for the computation (computational CPU time) is increased by increasing the grid-refinement number N. The computational error can be reduced by increasing N and can be as less as 1%. Future research will focus on making the technique universal, by considering tap layouts on surfaces with generic geometry. A mathematical formula that permits the calculation of the tributary areas of irregularly distributed pressure taps on surfaces may be attained in the future.

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