RTS measurement of aeroelastic effects on a 30m-high historical industrial chimney

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ABSTRACT

We used a robotic total station (RTS), or robotic theodolite, or Total Positioning System (TPS) with a frequency of 2Hz to measure the instantaneous deflections at the top of one of the three 30m-high historical brick chimneys in the Gazi area (historical center of Athens) because of wind excitation. Measurements were made on reflectors already established on the top and the middle of these chimneys in the framework of a project to monitor their subsidence and tilting during the excavation of a line of the Athens Metro. Geodetic measurements were made under favorable meteorological conditions during four intervals, half to one hour long, during which the wind force 5- 6 in the Beaufort scale velocity was fluctuating from a nearly stable direction, as indicated by recordings of a nearby meteorological station. The output of this study is that during this rather common wind event deflections of the top of the chimney along and across the direction of the wind were above the noise level by a few mm and reflected aeroelastic effects, including Karman vortex vibrations. However, the correlation between dynamic deflections and variations of the amplitude/direction of the wind is not clear, probably indicating deflections due to gusts, not described by the available low-rate wind data. This implies that various historical slender structures such as columns and minarets are excited by wind effects, which may represent a cause for their destruction.

I. INTRODUCTION

Theoretical models and field evidence indicate that tall slender structures are subject to aeroelastic effects, i.e. oscillations produced by the wind, but the available information is practically limited to modern metallic or concrete structures (Holmes, 2015; Bachman et al., 1977). For this reason, the response to wind of ancient and historical slender structures such as tall columns, tall industrial chimneys and minarets is not known, and hence it is not known whether wind effects may have been the cause of their destruction. The main reason for that is that no measurements of response of such structures to wind effects have been made.

In this article we report the results of a survey focusing on dynamic deflections of the top of one of the three similar, 30m high, 19th century industrial masonry chimney (Fig 1a), in the center of Athens, in the Gazi area (Technopolis recreation and culture center). These chimneys are 3x3m wide at their base, apparently slender, and their excitation by wind is possible.

Our survey was made on May 30, 2005 during a period of moderate to strong wind and was based on Robotic Total Station (RTS) (or robotic theodolite, or TPS Total Positioning System) and on prismatic reflectors fixed on the top of the K2 chimney (proximal to Piraeus St.; Fig 1b).

RTS have a sampling rate up to 5-7Hz and for this reason they have been used for monitoring dynamic displacements usually of flexible structures such as long bridges (Lekidis et al., 2005, Erdogan and Gulal, 2009), but also of stiffer structures with sub-cm deflections (Stiros and Psimoulis, 2012; Moschas and Stiros, 2014).

This study proved extraordinary for two reasons. *First*, the three chimneys in the Gazi area are historical, protected monuments, and any access on them is not allowed. This prevents any measurements with RTS. However, our survey was made possible because we used geodetic reflectors which had already been mounted on two of these chimneys using alpinist techniques, in the framework of a project for the monitoring of the tilting of these chimneys in response to tunnel excavation for the Athens Metro Line 3 (Papastamos et al, 2015). *Second*, we have tried several times to measure wind-induced deflections of the chimneys in the Gazi area planning field surveys when strong winds were expected, but we have been lucky only once, during a survey in May 20, 2005, when strong wind was flowing (maximum recorded velocity of the order of 9m/sec recorded in the National Observatory of Athens - NOA station, one kilometer away, corresponding to wind of Beaufort force 6).

A first output of our study is that Robotic Total Station (RTS) are suitable for the monitoring of dynamic deflections of slender structures such as old industrial chimneys.

A second output is that brick-chimneys of this type are sensitive to aero-elastic effects, and in fact their dominant vibration is due to Karman street vortices.

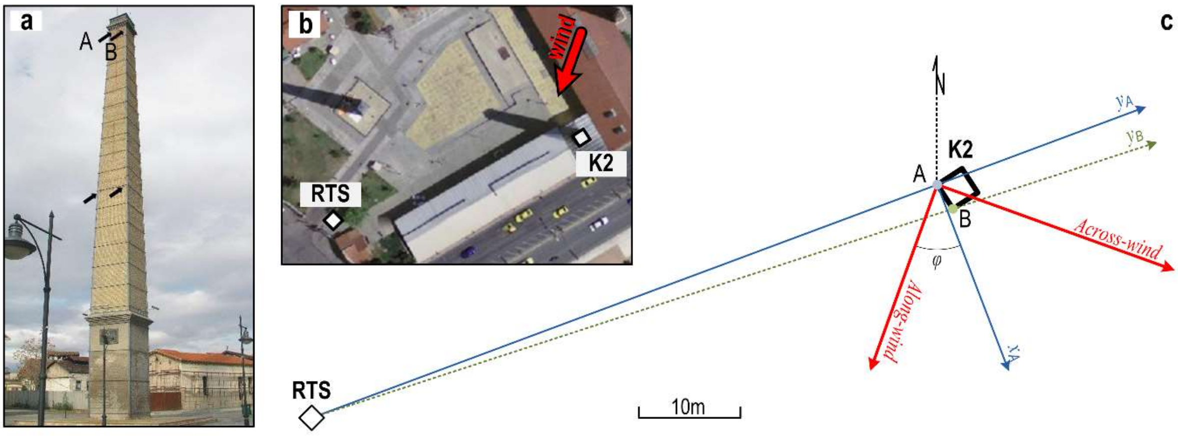

Figure 1. (a) The 30m high, 19th century industrial masonry chimney (K2) in the center of Athens. The arrows at the top indicate the position of the reflectors (A and B) that were monitored during our field survey. (b) Google map aero-photography of the study area showing K2 chimney, the location of the RTS and mean wind direction. (c) Details of the local survey coordinate system. Target A on top of K2 chimney was measured during the first three measurement intervals, and B on the 4th. Local coordinate systems for sighting targets A, B, global coordinate system and wind direction are also shown.

A third output is that this study confirmed previous results that there is usually poor correlation between dynamic deflections of structures and conventional (low frequency sampling) wind measurements (Han et al., 2016; Brownjohn et al., 2014), especially if the latter are collected at some distance from the study area. The output of this study is also consistent with the conclusion that dynamic deflections of structures are especially associated with gusts, recorded only by high-frequency instruments (Thalla and Stiros, 2018).

II. FIELD SURVEY AND DATA COLLECTION

Our survey measurements were based on a Robotic Total Station (RTS) sighting to a reflector fixed on the upper part of the studied chimney (Fig 1a). A LEICA TCA 1201 RTS, with built-in software upgraded to record measurements with a resolution of 0.01sec was used (cf. Stiros and Psimoulis 2012). The RTS was setup on a tripod on stable ground, near the main entrance of the Gazi complex, approximately 65m from chimney K2 (nearest to Piraeus Street), in a site somewhat protected from wind. The selected setup point permitted also undisturbed view to two prismatic reflectors (A, B) fixed on the same face of chimney K2, near its top. Reflector A was sighted during the first three survey intervals, and B during a fourth interval. For all four intervals, the RTS center and the mean coordinate of the reflector were used to define local cartesian coordinate systems, and to record instantaneous coordinates of the sighted reflector.

Measurements were collected with a mean frequency of 2Hz. Each measurement interval lasted between 25 and 69 minutes (Table 1), covering in total an about 5-hours long survey.

Wind data come from the station of the NOA, at an elevation of 10m from the round, 1.1km away from the Gazi area. The available data, wind velocity and direction relative to true north, cover the whole interval of measurements, with a frequency of one measurement per minute. Such sampling rate clearly does not describe high-frequency wind effects (gusts) which affected the Gazi area during the survey, as was felt by the survey party and as is derived from a longer-term experience from the study area. In fact, the available wind record contains a maximum instantaneous value of wind velocity of 11m/s during the second interval, apparently associated with a gust, while mean recorded wind velocities were about ~6.0-7.5m/s (Table 1).

Table 1. Summary of observations of deflection and of wind characteristics during the four monitoring intervals (i1 to i4). Wind data based on NOA records, wind velocity adapted to the height of 30m. An overall stability in the wind direction is inferred.

	i1	i2	i3	i4
Reflector	A	A	A	B
x-axis azimuth a_x (°)	159	159	159	162
Duration (min)	37	50	25	69
Mean wind velocity (m/s)	7.6 ±0.9	7.5 ±1.3	6.2 ±0.8	5.7 ±1.2
Maximum wind velocity (m/s)	9	11	9	7
Mean wind direction a_w (°)	196 ±12	211 ±12	205 ±6	200 ±10
Maximum deflection along-wind (mm)	8	13	9	7
Maximum deflection across-wind (mm)	7	14	7	6

III. DATA ANALYSIS

For each survey interval, from the recorded data describing instantaneous positioning of the observed reflector, a mean value of the coordinates of the reflector was computed, and the axes of the local coordinate system were correlated with true North (Fig 1c). Then, for all four intervals, time series of instantaneous deflections of the reflector from its mean value were computed. For each interval, time series of instantaneous deflections (x, y) relative to the mean coordinate of each interval, became hence available. These deflections refer to local coordinate systems (Fig 1c, Table 1).

Following Eurocode 1 standard techniques, wind data collected at a height of 10m were transformed into wind values corresponding to the height of 30m (Eurodoce 1; Moschas and Stiros 2014).

Data and results for each interval are summarized in Table 1. Wind directions in each interval were limited to a range of ~±30°, indicating an overall stability in the wind direction for each interval, defined by a mean azimuth a_w.

For this reason, it was reasonable to transform the time series of deflections of each interval into time series of deflections along wind and across wind using a standard transformation

$$\begin{bmatrix} X \\ Y \end{bmatrix} = \begin{bmatrix} cos\varphi & -sin\varphi \\ sin\varphi & cos\varphi \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} \quad (1)$$

here x and y correspond to local systems of coordinate changes and X and Y deflections along and across wind direction, respectively, with φ defined by the equation

$$\varphi = a_w - a_x \quad (2)$$

where a_w is the azimuth of the wind direction and a_x the azimuth of the x axis of each local coordinate system.

Results for each of the four intervals are plotted in Fig 2, so that a possible relationship between the two components of deflections and wind velocity and direction can be derived. Deflections were also plotted in the hodographs of Fig 3, in which the mean direction of wind was also shown.

IV. DISCUSSION AND CONCLUSIONS

Previous evidence from the application of RTS in controlled experiments reveals that, even for higher sampling frequency (5-7Hz), the instantaneous coordinates obtained from sighting to very high-quality reflector is of the order of a few mm (Stiros and Psimoulis 2012), but this accuracy is expected to be reduced in the case of atmospheric turbulence. In the Gazi observations, common prismatic reflectors were used, but because of ground clearance and undisturbed sighting line, the uncertainty zone for our observations is expected to have a width of a few mm. This indicates that the relative dislocations of Fig 2 are significant, and they reflect "true" deflections because of the excitation of the chimney by the wind, both in the across-wind and the along-wind components.

Still, no clear correlation between amplitude of deflections and wind velocity is evident. This is not a problem, because similar results have been observed in other cases as well, for example in dynamic monitoring of bridges (Brownjohn et al., 2014; Saracoglou and Bergstrand 2015; Thalla and Stiros, 2018; Meng et al., 2018). There are two main reasons for that. A first reason is that observations come from a rather distant station, not fully representative of the wind conditions in the Gazi area, where wind was very strong, especially some wind gusts. This is probably due to local conditions tending to amplify wind in a site with a slight difference in the elevation only from the NOA station, as is derived from empirical observations during other periods as well. A second reason is that deflections of structures are likely to be associated with wind gusts (Thalla and Stiros, 2018), but gusts are filtered in our low-frequency record (sampling every 60sec).

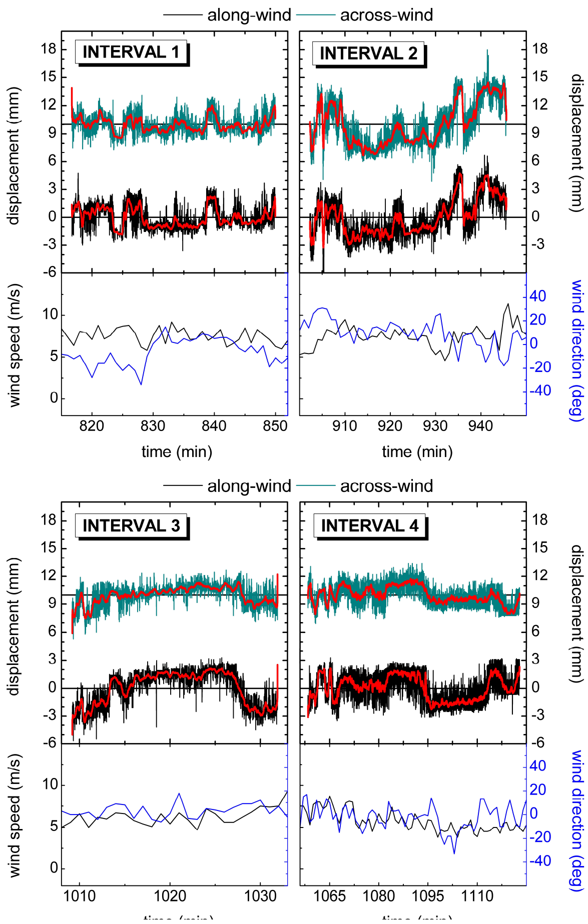

Figure 2. Along and across-wind deflections of the chimney and wind characteristics (black line indicate velocity, blue line deviation from mean direction). A red line indicates the long-period displacement of the top of the chimney. Deflections are significant both concerning the across-wind and the along-wind component.

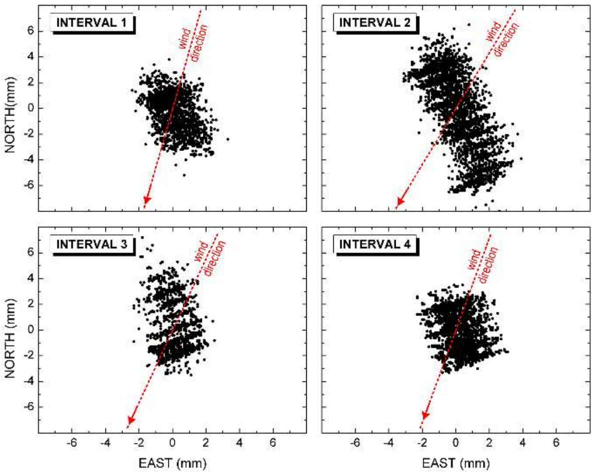

Figure 3. Hodograph (East-North plot) of the instantaneous deflections of the top of the chimney. Mean wind direction is shown. Dominant cross-wind deflections are evident during Intervals 2 and 3.

Another main result is derived from both Figures 2 and 3. Fig 2 shows that apart from a component of deflection along the wind, there exists a component normal to the wind as well (cf. Table 1). Fig 3 shows that the across-wind component tends to be higher than the along wind especially during the 2nd and 3rd interval. This is expected and is likely to correspond to Karman street vortex effects which have been well-documented in various modern tall, slender structures usually made of concrete and steel (Bachmann et al, 1977; Holmes, 2015). However, because of the low sampling rate of the wind (1 measurement per 60seconds) and the relatively low sampling rate of the RTS (2Hz), no details of the characteristics of these aeroelastic effects are possible.

New evidence from the Gazi project indicates that ancient and historic structures such as chimneys, columns, minarets etc. are subject to wind-generated vibrations, both in the along-wind and cross-wind direction. Such oscillations may represent a potential threat and a reason for the collapse of ancient buildings.

V. Acknowledgements

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