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COMPREHENSIVE AERODYNAMIC AND DYNAMIC STUDY OF INDEPENDENCE OF UKRAINE MONUMENT

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Comprehensive approach for solution the engineering problems of creation the high-rise extended pillar type Monument in Kiyv is described. The results of dynamic tests of 1:25 scale model and aerodynamic tests of 1:8 scale model of the Monument in TAD-2 wind tunnel are given. The procedures for determination of actual dynamic characteristics and assurance the efficiency of damping on the site are described.

Introduction

The pillar-type monuments are constructions, which have always been widely spread in the world practice. If their dimensions are comparatively small, stone is selected as a material for their construction in accordance with century-old tradition. In this case, more often than not, there are no serious problems as to provide strength, stability and reliability.

It is a more complicated case, when the architect's concept implies an erection of high-rise extended monument with limited transverse rigidity. For such kinds of monuments a horizontal wind actions may be regarded as decisive, and it is inexpedient, or merely impossible to apply traditional solution. In particular, at present it is not reasonable to construct a high pillar made wholly of granite. It would be highly labour-intensive and expensive.

Engineering solution

In Kiev, the capital of Ukraine, in commemoration of the tenth anniversary of Independence declaration, the Monument was erected in summer 2001. It is a high-rise column with a sculpture, symbolizing a young revived State of Ukraine on its top (fig. 1). The engineering solution of column is as follows: it is made of metal-latticed pillar, 2,56 m in diameter with granite facing, placed at reinforced concrete pedestal at elevation 12 m.

The pillar is crowned with a capital at elevation 50,25 m. The bronze sculpture is installed on the capital. The height of the entire sculptural composition is 11 m. The metal pillar is designed in the form of a regular octahedral prism with chords made of welded flange beams. It is provided with circular diaphragms, with 3 m by height spacing is, and cen-

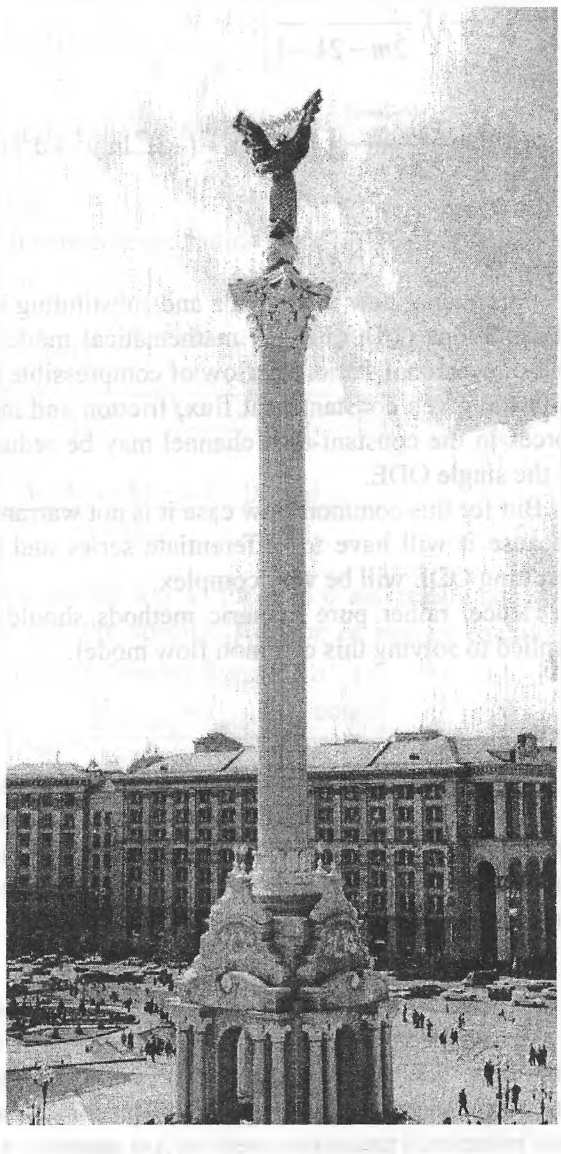

Fig. 1. General view of the Monument

tral block of spiral stairs. The circular diaphragms are intended for hanging of granite facing plates on them. A lot of modern technologies have been successfully implemented in recent years for construction of many projects with stoned facing. In our case, granite plates are attached to the framework with application of so-called "dry" assembly method, using special filling fastenings. This "dry" assembly method makes it possible to avoid the use of wet processes during erection of plates and sealing.

One of the engineering problems to be solved in the design of the pillar was to guarantee its dynamic stability in the wind flow. High-rise constructions of a similar kind, such as, for example, television towers, mast antennas, round shape chimneys and the like refer to a class of aerodynamic bluff bodies. When the air is flowing around a tubular-type object, a regular vorticity under specific flow conditions appears (so-called Karman's tracks), resulting in the swing of the structure in a across-flow direction and giving rise to cyclic dynamic stresses in its members. These cyclic stresses are hazardous from the viewpoint of fatigue strength and may lead with time to the development of cracks in metal and welds. Sometimes it gives birth to the monument failure or its fragments, which took place in several cases at real projects. That is why in order to provide guaranteed reliability under the operational conditions of the Monument, the provision was made in the designing process for anti-vibration protection of the structure in the form of mechanical damper, positioned at the upper part of the pillar (fig. 2).

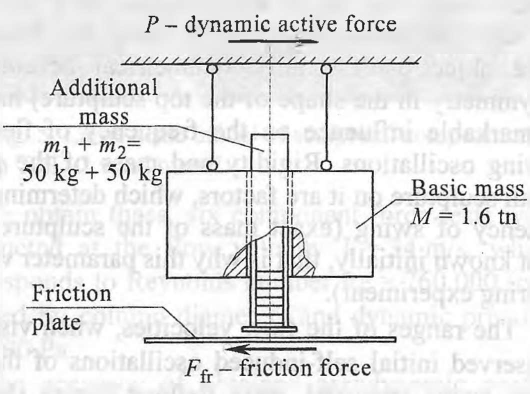

Fig. 2. Pendulum-type mechanical damper

The damper used may be referred to a pendulum-type damper, which swings in anti-phase with column oscillations, caused by exciting effects. The damper's mass may oscillate in any direction and, thereby, damp transverse swings under resonance. In addition, it makes possible to reduce dynamic component of wind load along the wind flow direction. In this design, a damper with frictional device and mass, consisting of two parts, is used. Namely: basic mass is attached to the Monument framework in the upper part using suspension, and additional mass slides along the friction area. This additional mass is attached to a basic one in such a way, that both masses may move jointly in horizontal direction only, and in vertical direction they are displaced independently. The damper's swing frequencies may be regulated both by changing suspension length and by adjustment of additional mass value. The magnitude of damping is specified by additional mass value also.

Such structural solution provides an opportunity to make fine adjustment of the damper and, thereby, to provide its optimal operation. Taking into account that in accordance with calculations, an occurrence of wind resonance is expected at the first tone of the Monument's natural oscillations, the adjustment of the damper has been performed exactly to the same frequency. Installation of the damper does not eliminate the problem of dynamic swings of the objects, but only reduces their intensity under correct adjustment.

Wind tunnel research

The analysis of the gained worldwide and domestic experience has shown that special attention should be paid to guaranteeing structural reliability for long-term service period. The main task is, to provide the fatigue strength of the metallic carrying framework under dynamic action of wind load. The problem has been set up to obtain reliable information concerning the following factors. Therefore, under review there was the following:

– real air flow regimes around the Monument, whereby self-excited swinging arise;

– real aerodynamic loads acting on the sculpture;

– real ability of the structure to suppress swinging (determination of actual damping decrement for correct assessment of the level of dynamic stresses component in structural members);

– full-scale frequency characteristics of the structure for availability to fine adjustment of mechanical damper system.

Dynamic tests. the first of the above-mentioned problems was solved by investigation of 1:25 scale aeroelastic model of the monument (fig. 3) in TAD-2 wind tunnel of National Aviation University. The experimental study using the model has been carried out at the Aerodynamics and Flight Safety Chair of the university according to the following procedure. Elastic-similar model was manufactured with strictly following the criteria of similarity. In particular: geometrical shape (K_l=1:25), mass ($K_m=R_l^3$), wind speed (accepted as K_w=0,9), flexural (K_{ei}) and torsion (K_{gi}) rigidity, ($K_{ei}= K_{gi} = K_l^4 \cdot K_w^2$), oscillation frequencies ($K_p= K_w/K_l$).

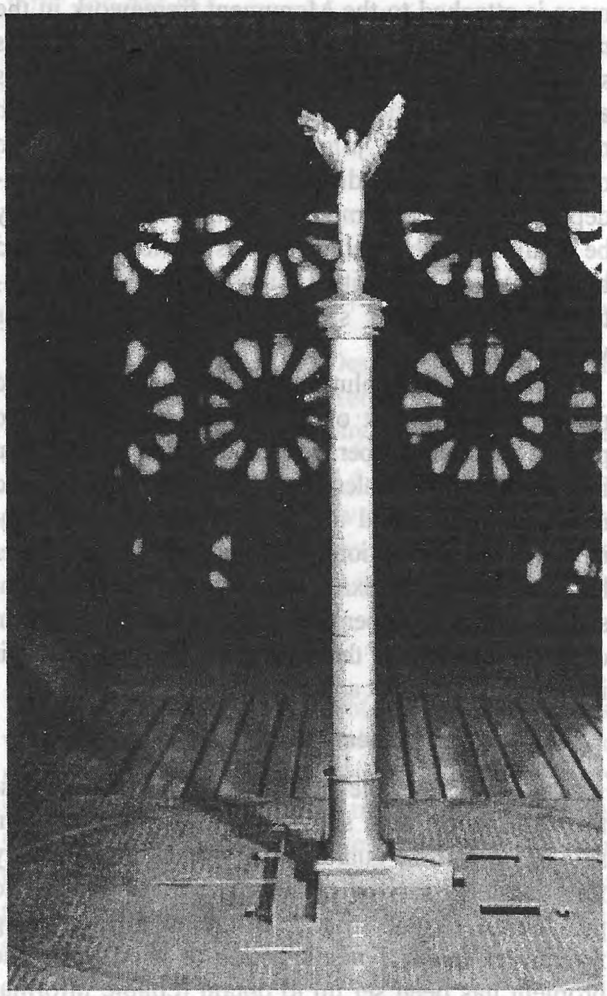

Fig. 3. Aero-elastic model of Monument column in TAD-2 wind tunnel

The principal scale factor KL was chosen to accommodate the model in TAD-2 wind tunnel test section (4 × 2,5 m). It should be pointed out here that TAD-2 is the largest wind tunnel in Ukraine. It is of open-return type, that permits various testing conditions including two-phase flows (icing and rain simulation), and easy flow visualisation.

The model of the object is a specially developed construction, consisting of central cantilever bar, which has simulated rigidity parameters of the system, and incorporates sections-compartments (12 by height). The last ones are fixed to the central bar and simulate the outer dimensions of the pillar as well as mass distribution along the pillar height (with the help of superimposed lead weights). As a model of the top sculpture, one of the transient plastic sculpture models was used (1:25 scale). On the central bar of the pillar model two strain gauges were mounted and connected to a computer-based data acquisition and processing system. The oscillation frequencies were obtained using discreet Fourier transformation of time series of strain gauge signals. Both time series and spectra were plotted (fig. 4).

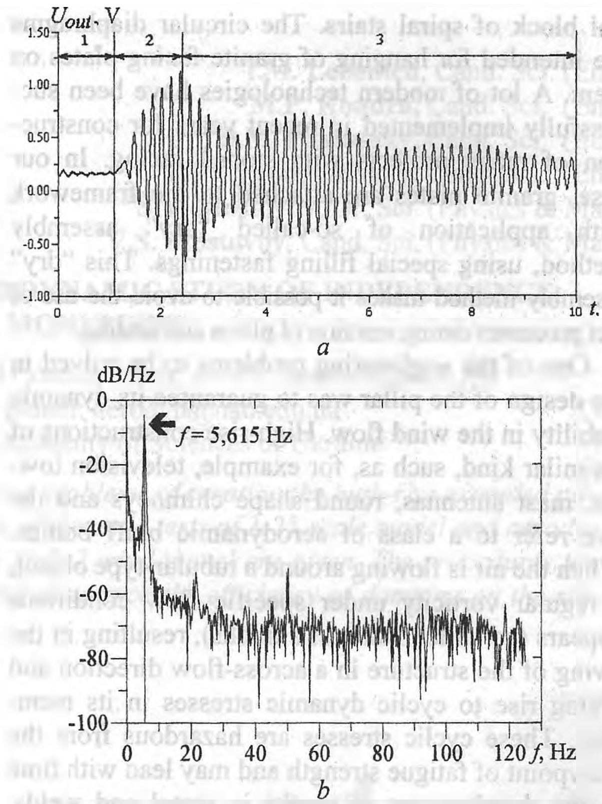

Fig. 4. Typical time series (*a*) and spectrum (*b*) of oscillations of elastic model of Independence Monument column (test protocol #P1004180, V=14,4 m/s, wind azimuth β = 180°):
1 – initial self-induced oscillations; *2* – induced-by-hand oscillations; *3* – free decaying

Analysis of the results showed that only the 1st tone oscillations in flexural swing for this particular object should considered to be significant. It was found that change of wind tunnel flow velocity (within the range from 0 to 28,3 m/s) and direction (the object isn't axially symmetrical because of asymmetry in the shape of the top sculpture) had no remarkable influence on the frequency of flexural swing oscillations. Rigidity and mass of the pillar with sculpture on it are factors, which determine frequency of swing (exact mass of the sculpture was not known initially, that is why this parameter varied during experiment).

The ranges of the flow velocities, when visually observed initial self-induced oscillations of the 1st tone swing occurred, were defined during the experiments as follows: 11–20 m/s when the flow direction was at the rear and on the side, 22–28 m/s when the direction was at the front and on the side. It should be thought that excitation of this oscillations were due to stalling characteristics of sculptural composition which is of asymmetrical shape with some parts projecting beyond and backward. The subsequent increase of current flow velocity resulted in gradual growth of oscillation amplitudes without their abrupt alteration.

Wind loading investigation. TAD-2 wind tunnel was also used to solve the problem of assessment the real aerodynamic loadings acting on the top sculpture composition. It is made in the form of a thin bronze shell welded from separate cast elements on a supporting steel frame structure. Such an engineering approach is used when sculptures are large enough and wind loads are large too accordingly and the task arises to minimize stresses in welded seams (not enough reliable) by using strong supporting structure. Internal space of the top sculptural composition is cramped that results in additional constraints to the integration of supporting structure in it. In our case, this is made of stainless steel tubes to provide long lifetime. The diameter of the main strut welded tube is 800 mm. The most crucial place in the supporting structure is the flange unit by which the structure is fitted to the column frame. Setting up the loads for strength calculation, which would be close to really existing, is very critical. Therefore, the aim of aerodynamic testing of large-scale (1:8) model of sculptural composition (fig. 5) was to determine aerodynamic forces and moments for all wind directions (circular blow round).

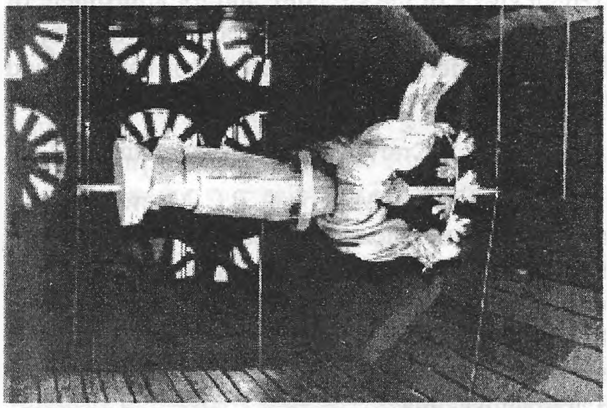

Fig. 5. Large-scale model of sculptural composition in TAD-2 wind tunnel

To obtain these, six component force tests were conducted at the flow velocity $V = 34$ m/s, which corresponds to Reynolds number Re = 760 000 (calculated by column diameter) and dynamic pressure $q = 700$ Pa.

The accuracy of obtained aerodynamic coefficients of wind loadings was guaranteed by a complex of measures. First of all the calibration of 6-component strain gauges and dynamic pressure transducer were conducted. These showed that relative error of loading measurement along wind direction axis Ox_a was equal to 0,3% and in perpendicular lateral direction axis Oz_a – 0,2%. The absolute error of the dynamic pressure transducer was 0,7 Pa which corresponds to the relative error of 0,1% for dynamic pressure q = 700 Pa. Secondly, the data acquisition and processing software was specially upgraded to obtain random errors of measured coefficients not greater than 1/3 of listed above instrumental errors, which were treated as residual systematic ones. In this case, it can be considered, that aerodynamic coefficient errors are fully determined by the systematic values mentioned, and absolute errors of force coefficients, being calculated in a usual way, were: for longitudinal force coefficient $\Delta c_x = 0{,}005$, for side force coefficient $\Delta c_z = 0{,}009$. It was confirmed by small discrepancies between separate segments of the curves obtained in different wind tunnel runs, as could be seen in fig. 6.

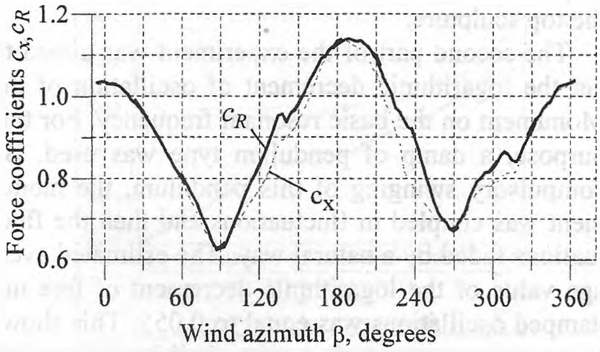

Fig. 6. The dependence of drag force coefficient c_x and total horizontal force $c_R = \sqrt{c_x^2 + c_z^2}$ on wind direction

The analysis of the results of conducted force measurements showed, that the largest wind loadings occurred with frontal wind directions: to the back ($c_x = 1{,}13$) and to the face ($c_x = 1{,}04$). With sideways directions these loadings reduce to $c_x = 0{,}65...0{,}68$.

Based on the data obtained in wind tunnel tests bending moment and other loadings were determined in the Monument fitting assembly, which were used as a basis for the check calculation of strength of flange unit.

Measurements on the site

With the purpose to get the Monument spectral characteristics, logarithmic decrement of the oscillations of the object and to analyse damping ability of the system, which was realised at the Monument for oscillation reduction, the site tests were carried out. For registration of fluctuations three-directional geophone with gauges located on three mutually perpendicular axes was used. The spectral characteristics of gauges represent one-modal curve with the extreme point in f=1 Hz. Geophones were placed on a horizontal surface, on the level of 42 meters. They served as a part of interface of the monitoring registration and processing automated system. This system allows to correct the spectral characteristic up to uniform in the chosen range of frequencies. The first part of experiment consisted in registration of monument reaction on a natural background as an input signal. This signal represents a superposition of the large number of the external factors from natural microseism noise and men-made one up to signals from ground transport. The important moment is that the total spectrum of these signals is much wider then the response spectrum of the Monument. For the Monument, three modes were obtained with frequencies of 0,48 Hz, 0,93 Hz and 1,47 Hz and corresponding amplitudes 1,0, 0,07 and 0,12. The frequency of 1,47 Hz with rather intensive amplitudes hypothetically is devoted to the mode of the top sculpture.

The second part of the experiment was aimed to get the logarithmic decrement of oscillation of the Monument on the basic resonant frequency. For this purpose, a damp of pendulum type was used. By compulsory swinging of this pendulum, the monument was coupled in fluctuations and then the fluctuations faded by a natural way. The estimated average value of the logarithmic decrement of free undamped oscillations was equal to 0,055. This shows that metal column with granite shell has rather low capacity to dampen fluctuations. The damper, when it was actuated during the tests, has increased the ratio of the logarithmic decrement of the oscillations up to the level equalled to 0,18–0,25. The damper gives the possibility to obtain greater ratio of logarithmic decrement of the oscillations by increasing of the friction coefficient of the energy absorber.

It's necessary to note that the spectrum of structure oscillations is its steady characteristic. This function varies with the change of mechanical parameters of a structure and can be used for detection of "age" changes of a structure during the period of lifetime. It's possible to consider that obtained spectral characteristics of the Monument can be used in future as reference data for detection of the Moment "age" changes during a structure-monitoring period.

Conclusions

The comprehensive methodology of aerodynamic and dynamic characteristics investigation was developed for high-rise column-type monument using wind tunnel aerodynamic force tests, dynamic test of aero-elastic model, and on-site measurements. For the Monument of Independence of Ukraine, erected in Maydan Nezalezhnosty square in Kiyv, the actual wind loadings on it and its dynamic oscillatory characteristics were obtained which were used for strength check of the structure and for adjustment of the damper in order to ensure safety of the object during long lifetime in the presence of natural wind disturbances.

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Комплексні аеродинамічні і дінамічні дослідження монумента незалежності України

Розглянуто результати комплексних досліджень вирішення інженерної проблеми створення висотного монумента колонного типу в Києві, динамічних досліджень моделі в масштабі 1:25 та аеродинамічних досліджень великомасштабної моделі (1:8) в аеродинамічній трубі ТАД-2 Національного авіаційного університету. Наведено процедуру визначення на натурному об'єкті реальних динамічних характеристик та забезпечення ефективності демпфірування.

И.Н. Лебедич, М.П. Кондра, Р.Н. Павловский, П.М. Виноградский, С.В. Мостовой, В.С. Мостовой

Комплексные аэродинамические и динамические исследования монумента независимости Украины

Рассмотрены результаты комплексных исследований решения инженерной задачи создания высотного монумента колонного типа в Киеве, динамических исследований модели в масштабе 1:25 и аэродинамических испытаний крупномасштабной (1:8) модели в аэродинамической трубе ТАД-2 Национального авиационного университета. Приведена процедура определения на натурном объекте реальных динамических характеристик и обеспечения эффективности демпфирования.