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Dynamic Evaluation of the Solar Chimney

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(This paper was reviewed specifically for the 3rd Young Engineers, Practitioners and Technologists Conference)

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The study scrutinises each of these terms individually in the context of the solar chimney as designed to date. A dynamic analysis is undertaken with all the above-mentioned parameters as defined and estimated by the study. In load cases where the wind direction inverts along the height, higher eigen-modes are amplified. However, the most severe dynamic amplification occurs at the fundamental eigen-mode. In the context of solar chimney research, this study brings valuable new insights regarding the dynamic behaviour of the chimney structure to the fore.

DYNAMIC EVALUATION OF THE SOLAR CHIMNEY

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Abstract: *Previous studies on the solar chimney, a reinforced concrete tower of 1500m high, internal diameter 160m, have shown that its structural integrity might be compromised by the occurrence of resonance. The wind gust spectrum peaks near the solar chimney's fundamental resonance frequency. This phenomenon poses a reliability threat, not only to the solar chimney, but also to all high-rise, slender structures. The dynamic equation of motion incorporates four terms that bind the factors responsible for resonance: accelerated mass energy, dissipated energy (damping), stiffness energy and input energy (loading). The study scrutinises each of these terms individually in the context of the solar chimney as designed to date. A dynamic analysis is undertaken with all the above-mentioned parameters as defined and estimated by the study. The results from the analysis show amplifications of approximately three times the static displacements. In load cases where the wind direction inverts along the height, higher eigen-modes are amplified. However, the most severe dynamic amplification occurs at the fundamental eigen-mode. In the context of solar chimney research, this study brings valuable new insights regarding the dynamic behaviour of the chimney structure to the fore.*

INTRODUCTION AND BACKGROUND

Higher and Higher

The time of super structures is upon us. No more fictional star wars like high-rise skyscrapers, fiction is turning into reality. With the assistance of computer power today, engineers are able to design buildings of larger proportions than before. There is no need for over-simplification anymore. Today it is possible to simulate a physical structure, in the finest of detail, on a regular desktop pc. Civil Engineers have acquired the ability to predict structural behaviour with accuracy, based on design and computational modelling. Only in exceptional cases it is required to study behaviour by physical, scale modelling. And it is not surprising that developers have the confidence to go wider, larger, and higher. Is it possible, even with advanced design capabilities and descriptions of nature, to build structures of limitless proportions today, unlike the ancient builders of the tower of Babylon?

Background to the solar chimney

In the past ten years universities in Germany, Australia and South Africa have been doing research on the feasibility of a Solar Updraft Tower, or solar chimney. The system will produce energy by means of updraft airflow from under a glass collector through a chimney, turning turbines that generate power. One such system can generate at a constant rate of 200MW throughout the day and night. Schlaich Bergermann und Partner is the leading engineering company in promoting the concept to potential energy users (Schlaich et al, 2004).

The challenging component of the system is the tower or chimney. The planned reinforced concrete chimney will be a freestanding structure reaching to a height of 1500m. According to Schlaich Bergermann und Partner "towers 1000m high are a challenge, but they can be built today".

"What is needed for a solar updraft tower is a simple, large diameter hollow cylinder, not particularly slender, and subject to very few demands in comparison with inhabited buildings." (Schlaich et al, 2004). Since the publication of the first concept the height has increased to 1500m, where a higher efficiency will be reached.

The peak power output should be achieved with a chimney of 1500m in height and a collector 7000m in diameter according to Schlaich (1995). With these dimensions the power output is large enough to be compared to the efficiency of small coal-fired power plants and small nuclear plants. The concept was presented to various countries around the world with the hope that someone somewhere would consider funding the construction of a full-scale prototype. It was during this marketing campaign that more questions were raised on the reliability of the project. The fathers of the solar chimney concept gave little attention to the scale of the structure they wanted to build. In their minds it was a fairly simple matter: construct an upright cylinder 1500m tall in a desert. But to a structural design engineer such a request is not as simple as it seems. And with questions such as the construction feasibility, a new generation of research studies was undertaken concerning the structural viability of the solar chimney.

Researched concerns

Stellenbosch University has participated in the project for numerous years, working closely with their German colleagues searching for solutions regarding the physical feasibility of the system. The departments of Mechanical, Electrical and Civil engineering have all contributed valuable research studies on the subject. In the past 6 years the following research has been done regarding the structural validity of the chimney:

- Structural integrity of a large-scale solar chimney (C. van Dyk, 2002)
- The realization of the solar chimney inlet guide vanes (C. van Dyk, 2004)
- Optimization of wall thickness and steel reinforcing of the solar chimney (M. Lumby, 2003)
- The development of ring stiffener concept for the solar chimney (E. Lourens, 2004)
- Wind effects on the Solar Chimney (L. Alberti, 2004)

These studies placed the complexity of engineering such a structure under the spotlight, but all of these aspects are related to design variables, which are concrete and very possible to define with enough research and detailed design. It has also been shown that the construction of such a large chimney might indeed be possible. However, the conditions regarded in these analyses are ideal, neglecting complex environmental actions. Although the danger of resonance due to wind loads was identified, simplified methods of wind loading were used, probably conservative. Environmental actions should be characterized to refine the prediction of the response of the structure. Thus, the limit of the domain of applicability of engineering models has been reached and must be extended to prove the integrity of the solar chimney tower.

CHIMNEY AND TOWER DESIGN

The science behind chimney design developed independently of concrete skyscrapers. Modern industrial tower designers have to deal with problems such as thermal variations over the height, chemical reactions with the building material etc. Modern TV towers have a new spectrum of criteria to be met regarding broadcasting equipment. It was not until the development of radio and television technology that the height factor in tower structure design came to the forefront once more. The 1970's saw a boom in the construction of radio and television towers world wide, the one being taller than the other. Most of these types of towers have observation decks or revolving restaurants and are therefore under high constraints with regard to movement. Both towers and chimneys are slender structures. They are the best examples of similar structures to the solar chimney. It is therefore important to study the design methods of these structures in the light of the solar chimney design, as these structures' main load source is also wind.

Identifying Resonance Modes

The first important characteristic of a structure that is subject to dynamic loads is its modes of resonance. The mathematical problem used to solve resonance modes (also known as 'fundamental' frequencies) is called the eigen-value problem. In the 1950's Arnoldi, Francis, Givens, Householder, Kublanovskaya, Lanczos, Ostrowski, Rutishauser, Wilkinson, and many others further developed algorithms and analysis for complex eigen-problems (O'Leary, 1995). Although these pioneers furthered the development of eigen-value analysis from a few differential equations to large systems, their work was only implemented in the engineering industry during the late 1970's with the development of desktop PC's. Until then simple hand calculations were used to estimate the vibration modes of structures.

It was not necessary to use complex eigen-solvers during the early years of dynamic computations.
Structures such as chimneys and TV towers could be modeled with simplified mathematical models, only incorporating the most important global degrees of freedom, limiting the number of differential equations to a manageable amount. Furthermore, it was widely accepted that only the first fundamental vibration mode was of importance to resonance. As a result simple algorithms were used in chimney design to estimate these vibration frequencies.

Incorporating Damping

As early as scientists realised that structures can resonate, it was also discovered that other energy losses exists in a system (mostly a combination of aerodynamic damping and structural damping). These energy dissipaters were modelled as one energy term in the dynamic equation in order to simplify the complex damping phenomenon. The result of this is that damping could not be calculated accurately as there are many unknown energy dissipation role players in this one mathematical term. The only way of knowing how large the 'energy extraction' of such dissipaters is, is to measure the decay of a structure's oscillating motion. Such tests serve as a database for future designers to consult in predicting the damping in a new structure.

Wind loads

Wind effects studied in tower and chimney designs include static wind loads, gusting dynamic wind effects, vortex shedding and ovalisation effects due to a distribution pressure around the shell. In towers and chimneys vortex shedding is often the most critical. These dynamic phenomena may lead to resonance and failure, despite sufficient resistance to static wind loads. A commonly used static wind load formulation is the power law profile.

Since gusting winds are unpredictable they are usually dealt with in a probabilistic approach. From statistical data reworked from measurements, hand calculation methods have been developed to simplify this complex phenomenon. A.G. Davenport (1967) proposed one such method known as the gust pressure factor approach. The static is wind profile is multiplied by a gusting factor, G.

Vortex shedding occurs as a result of vortices or eddies that form as air passes by the section profile. From the Strouhal number, the critical airflow velocity for a certain frequency can be determined. If the critical airflow velocity of the first mode's natural frequency is outside the reach of the mean airflow, the structure is safe.

Ovalisation occurs in sections with large diameters and thin walls. This can be the effect of airflow around the section and the resulting cantilever bending moment which warps higher circular sections on the free end of the cantilever. Bending moments form along the circumference of the section in the wall. In reinforced concrete cracks will form and reduce the stiffness. This threatens limit states as defined in building codes.

Design

Once the stiffness of the structure is determined, deflections can be calculated by applying static loads. The structure may be designed according to this criterion as long as the dynamic loads' frequencies are well out of range of the structures fundamental frequencies. The traditional methods of calculating these frequencies are very simplified. For more accuracy a full scale frequency domain dynamic analysis was performed on the solar chimney model.

THE FINITE ELEMENT MODEL

Although previous finite element models of the solar chimney exist, it was important to re-assess the effectiveness of the model in the light of a dynamic analysis. Dynamic analyses require more computing power, more time and more variables than just stiffness, displacement and load, as is the case with a static finite element analysis.

Mesh refinement

The solar chimney model is meshed with CQ40S quadrilateral isoperimetric curved shells. Each element has eight nodes and each node in turn has five degrees of freedom, three translational and two rotational. The in plane torsion degree of freedom is ignored. Such nodes are known as 'drifting' nodes. The structure has certain limitations regarding meshing, as certain nodes in the height axis and along the parameter is fixed according to the ring stiffeners situated on the inside of the structure. The ring stiffeners are spoke-like wheels placed horizontally at certain heights in the tower to minimize ovalisation. The nodes at these stiffeners are fixed in torsion in the vertical direction to simulate a drifting effect in the ring stiffener plane. In order to get an idea of the effect of different meshes the computed behaviour of the structure will be compared when finer meshed. An optimum mesh was chosen where the model behaves the least stiff.

The Eigen problem

In order to simplify the analysis, a frequency domain dynamic analysis was chosen to reduce computing time. A structure consists of various Eigen frequencies, or resonance frequencies. For each of these frequencies the structure will oscillate in a certain displacement pattern (Figure 1). This is known as the structure's Eigen modes, to which the various Eigen frequencies correspond. If the structure encounters a vibrating load with frequency components matching any or some of the structure's eigen frequencies, it will resonate to a greater or lesser extent in that particular eigen mode shape.

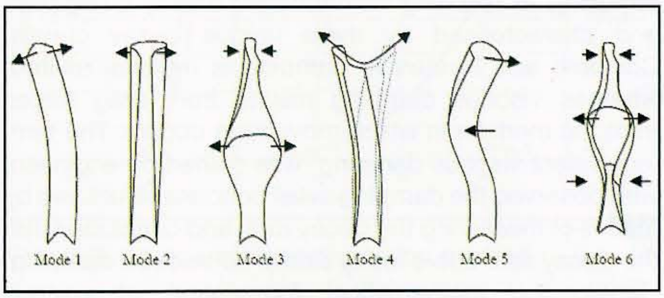

Figure 1: The first five Eigen modes

A mathematical model has as many Eigen frequencies as it has degrees of freedom. Each individual mode response is a vector of the global response. Every Eigen mode-shape carries a certain amount of the total resonating energy. At very high frequencies the displacement response is so small that they can be ignored for all practical purposes. Of the 6000 Eigen modes in the solar chimney only the first 400 was considered in the analysis, of which only 10 were global Eigen modes.

Proportional damping

Damping is the absorption of energy, based on a structure's material and geometric properties. In order for things to move, to flex, to crack etc. energy is needed. This requires energy to be taken out of the global motion energy of the structure. Hence the energy equilibrium with stiffness energy, momentum energy and damped or dissipated energy is taken from the initial energy put into the system.

The damping matrix is set up to enable the decoupling of the degrees of freedom. The damping matrix will be orthogonal if the orthogonal mass and stiffness matrices are multiplied by coefficients α and β. The damping is thus assumed to be directly related to stiffness and mass-kinetic energy.

ESTIMATING DAMPING CHARACTERISTICS

The estimation of damping in an untested structural geometry is a difficult matter. Although a variety of literature is available on the subject of damping, it remains a poorly known aspect of general vibration analysis. Woodhouse (1998) proposed that the reason for this is that a fundamental, universal mathematical model of damping forces does not exist, and needs to be characterized experimentally.

Understanding damping mechanisms

Various methods of modelling damping and their mechanisms have been proposed in the literature. The most general are Viscous, Coulomb and Hysteretic damping, all resulting from different energy dissipaters and characterised by there unique decay curves. Coulomb and Hysteretic damping is material related, whereas viscous damping results from drag forces from the medium in which movement occurs. The term 'equivalent viscous damping' was coined by engineers who observed the damping in tall concrete structures by means of measuring the decay rate, and concluded that the decay rate curve looks similar to viscous damping. Hence, the mathematical formulation of viscous damping is generally used in tall concrete structure analysis, although it is known that the damping sources are more hysteretic and coulomb related.

Measuring damping

As mentioned, damping mechanisms are characterised by their rate of decay. In the case of Viscous damping, the rate of decay is a logarithmic function, hence the term characteristic parameter – logdec. The logdec of a structure can be measured by observing the decay in oscillation when the first Eigen mode is activated (either by a instantaneous force or by a initial displacement). In turn, the measured logdec can be related to the ratio of critical damping (the least amount of damping needed to keep the system from oscillating in that particular mode). Critical damping in turn is a function of stiffness and mass.

For the dynamic analyses of medium height towers or chimneys, the logdec can be determined by comparing measurements of structures with similar fundamental Eigen frequencies and heights. In the case of the solar chimney, no structure of its magnitude exists. Thus, a logdec value had to be estimated by looking at smaller, existing structures with the same type of slenderness ratio, and close to the fundamental frequency of the solar chimney. A database of logdecs of the tallest TV towers and chimneys in the world was plotted against their fundamental frequencies, and a trend line extrapolated to the frequency of the solar chimney (Figure 2). Although the theory states that measured logdec is independent of frequency, measurements from different tower-like structures shows a tendency to higher logdec values with a decrease in the first eigen-mode frequency.

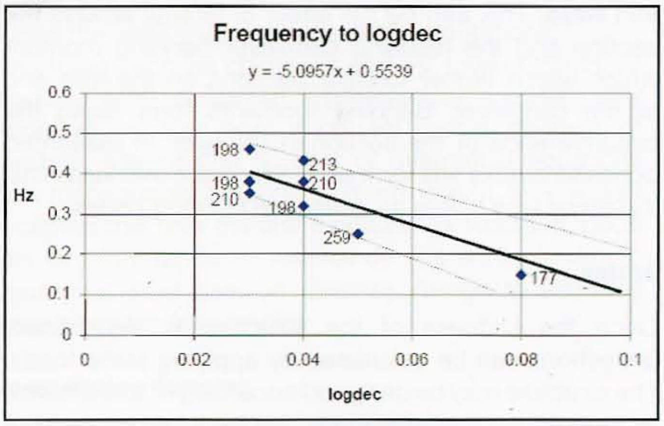

Figure 2: Linear estimation of the logdec at 0.1Hz based on existing tower measurements

From the available data, a logdec value of between 0.09 and 0.12 can be estimated for the fundamental vibration frequency of the solar chimney. This implies 1.43% to 1.91% percent of critical damping. This range agrees with the generally accepted range of damping ratio for concrete structures in the high amplitude range, as presented by Jeary (1986).

Rayleigh damping

Rayleigh's principle proposes to define damping as an energy loss due to a combination of a mass's movement through a medium and bending of a member or structural component. When a mass moves through a medium (like water or air), energy is lost because of drag. Little energy is lost because of small drag, resulting from slow movement. At high frequencies, more energy is lost because of higher oscillating velocities, resulting in higher strain and thus greater drag forces. Energy is transformed to heat when a piece of material bends in rapid succession as a result of internal material friction. Faster repetitive bending results in higher energy loss. Thus, mass proportional damping (β) damps out lower modes, where stiffness proportional damping (α) damps out higher modes.

Choosing values for α and β can be difficult for structures with many degrees of freedom. The choice of α and β determines the damping proportion of the uncoupled system's critical damping value. Hence mathematicians have developed calibration methods to compute α and β. One method, described by Chowdhury and Dasgupta (2003) is to calibrate the proportions by means of interpolating the modal damping ratio for each uncoupled equation based on mass participation (the ratios of participating energy in each Eigen mode). The mathematical formulation of Chowdhury and Dasgupta could be applied to compute the α and β terms of the solar chimney, in order to calculate the damping matrix.

From the author's frequency analysis results presented later it is shown that the second mode's resonance peak is about six times lower than the first mode. Furthermore, there are little signs of high frequency resonance even at 1% of critical damping. The need to damp out higher modes is therefore not critical, and the lower frequency modes are dominated by the first mode. The need for calibrating each modal damping value does not arise yet, but depending on the wind loads (described in the next section) it might become important in some cases.

CHARACTERISING WIND

The density of air varies in height, resulting in different wind speeds at different altitudes. In most cases, structural dimensions are so small in comparison to the scale of the differences in air movement, that it can be assumed the structure is experiencing a constant pressure load, uniformly distributed over the whole exposed area. However, skyscrapers and high towers experience a variation in wind speeds with height. Building codes prescribe a vertical wind speed profile for tall structures, but this profile is limited to the layer in which air movement is highly effected by ground friction.

Static wind profile

As mentioned earlier, the most commonly used wind profile is the power law profile. These types of formulations are subject to the effects of ground roughness and the boundary layer. This layer is more or less the height at which the effect of ground friction dies out (1km above ground), and the wind patterns are governed by geostrophic or gradient winds. Thus, 3 regions occur: friction influenced, boundary and geostrophic. The difference between geostrophic or gradient winds and wind in the boundary layer is the forces working in on a particle of air. Two characteristic length scales therefore affect the mean velocity curve. The surface friction close to the ground dominates the one and the other is dominated by the free flow at the top of the boundary layer.

The corrected logarithmic profile is a more precise expression for heights above 200m above the ground. Harris and Deaves (1980) developed the formula. This equation is valid up to the height where airflow becomes geostrophic and stabilizes in velocity over height. The wind speed is then a function of the local weather system and isobar gradient. The advantage of the logarithmic profile is that it can characterise wind velocity over two distinct air layers, tying it into the constant geostrophic region. The advantage of the power-law profile is its simplicity, fairly accurate up to 300m. Above this level the profile becomes very unrealistically exaggerated (Figure 3).

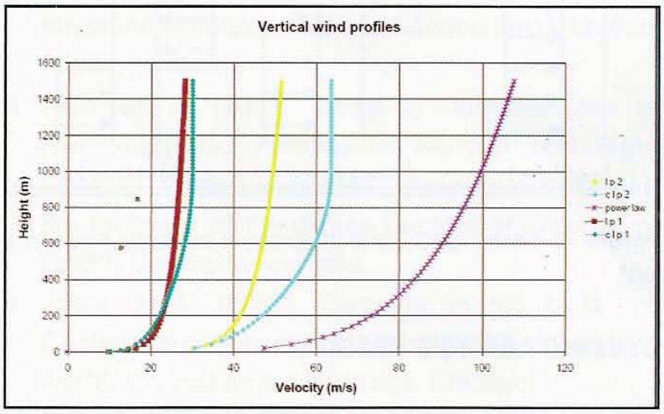

Figure 3: Comparative vertical wind profiles

Dynamic wind loading

The turbulence component shown in figure 5-1 is what causes the fluctuating nature of airflow referred to as gust. It is this component that will cause a structure to respond in a dynamic way. To characterise this behaviour is difficult, as gust is a random process. Its characterisation depends on the nature of the instantaneous fluctuations of pressure; hence it cannot be determined by normal averaging accelerometers. The whole process of obtaining data is unique in itself.

For application in the solar chimney analysis, the power spectral density function proposed by A.G. Davenport (1962) was used to generate an artificial wind gust history. This data was compared to measurements taken with a home-made accelerometer (working with a strange-gauge and being able to take 10 readings per second). As shown by the tests conducted at two gusty locations in South Africa, Davenport's power spectral density for gusting wind is a realistic description and applicable in the relevant frequency range.

Direction variation in height

From the meteorological knowledge of the Upington region, it can be shown that wind direction inversions are a frequent phenomenon as a result of temperature inversions. This can affect the response of higher modes in the solar chimney. To test this effect, three direction load-cases was applied at maximum gust speeds to amplify the effect. The first was in one direction only (LC1); the second turned 180 degrees at 750m (LC2); the third changed 180 degrees at 500m and changed back to the first direction at 1000m high (LC3). The third load case may result from airflow inversions due to thunderstorm activity (Figure 4).

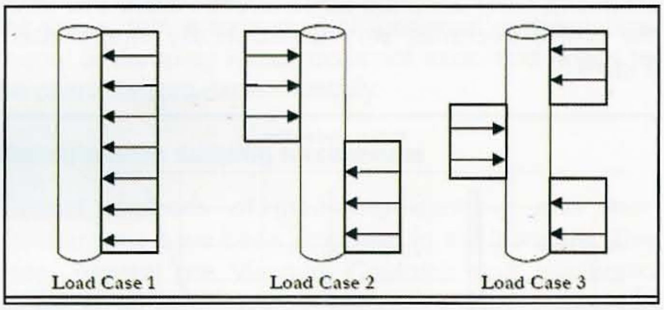

Figure 4: Three load case inversions (direction vectors only)

DYNAMIC ANALYSIS RESULTS

The maximum dynamic amplitude at 30m/s is 7.92m at 0.1Hz with a static displacement of 2.91m and the root mean square value (calculated from 0.01 Hz to 0.48 Hz) is 8.22m. At 42.5m/s the maximum amplitude is 35.8m at 0.1 Hz with a static displacement of 5.81m and the root mean square value (calculated from 0.01 Hz to 0.48 Hz) is 36.986m.

Damping Sensitivity

To estimate the effect of damping on the system, the simulation was done with varying damping values, ranging from 1% to 5% in increments of 1% (Figure 5). Although higher damping will occur at higher modes, the same percentage of critical damping was assumed for all modal frequencies, as the effect of the higher modes was very little even with low damping. Therefore, this approach can be considered as conservative concerning higher resonance modes. Between one and 3 percent of critical damping, the increasing effect of damping has a considerable effect on reducing the resonance amplitude. From 4% to 5% the amplitude decreases with 0.44m as opposed to a 3.58m difference between 1% and 2%. From 5% damping onward, the decreasing amplitude effect becomes small. At 5% damping the dynamic amplification factor is 1.6.

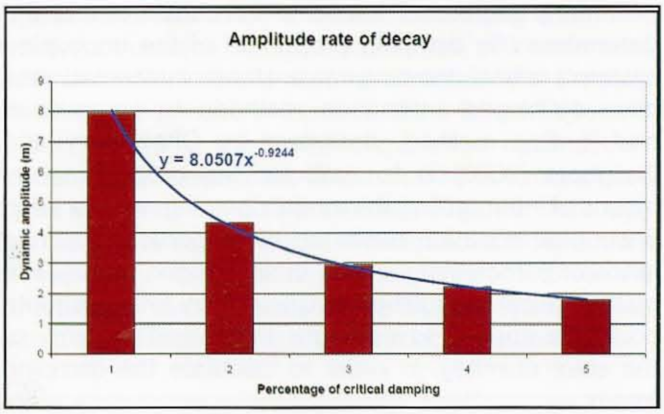

Figure 5: The decay rate of response amplitude

Inverting load directions

As a result of the change in direction, it is expected that LC2 and LC3 can amplify eigen-modes where the eigen-vectors correspond to the load vectors. LC3 resembles the fifth eigen-mode shape, thus it is not surprising that, even though the static response is less, LC2 and LC3 show much higher amplitudes at 0.33Hz (mode 5) than LC1. At 0.1Hz (mode 1) LC3 shows the smallest amplitude since the height of the top pressure distribution (that activates mode 1) is the smallest. At the static state, however, LC2 shows the smallest deflection as the resulting pressure load on the whole tower is minimal (Figure 6).

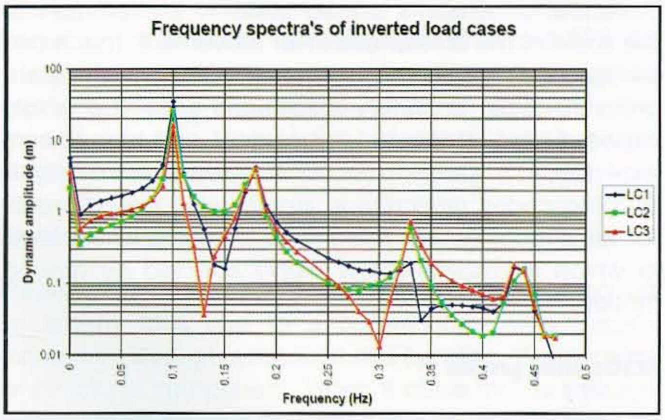

Figure 6: Log plot of LC1 to LC3

The amplitude response of LC1 at 0.33Hz is 0.19m. With LC3 it is 0.793, just over 4 times higher. Although these amplitudes seem small in comparison to the amplitude at the first mode (16.7m for LC3) it can still result in significant stress levels as the oscillation period is much less (3 seconds appose to 10 seconds) and the length over which the displacement occurs is much less (i.e. the curvature is larger for a given displacement).

Ovalisation

As a result of the pressure distribution around the parameter of the solar chimney and 2nd order reaction to bending, the circular section shape is warped. This is the same deformation industrial chimneys experience, as mentioned earlier. The difference is, in this case the warping is dynamic. As the wind gusts by the chimney and fluctuates in speed, the pressure distribution fluctuates as well. The resonance effect may be amplified if the frequency of vortex shedding is close to the frequency of the second eigen-mode.

CONCLUDING REMARKS

The goal of this study is to better characterise the dynamic response of the solar chimney structure, rather than to produce an exact result. Although the contributing factors in the dynamic force-equilibrium equation are not exact, a wide scope of new insight has been gained through this investigation.

From the results it can be concluded that noticeable resonance behaviour will occur at yearly reoccurring gusting speeds (30 m/s). At 50-year (or more) reoccurring speeds (45.2 m/s), as shown by records of the De Aar weather station, the resonance amplitude may exceed static limitations as defined in building codes, based on the slenderness ratio of the structure. Although these amplitudes are subject to the percentage of critical damping in the structure, which exact value is unknown, conservative projections of energy dissipation must be kept in mind when estimating conservative amplitudes, as these above-mentioned results are based upon.

The study highlighted the complexity in understanding, estimating and simulating the factors that contribute to dynamic behaviour. It is clear that noticeable resonance will occur, no matter how conservative these factors are regarded to be. The contribution of this study in the development of the solar chimney project is that it proves that dynamic behaviour will certainly be a consideration factor in the geometric design and the reliability estimation of the chimney structure.

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