DESIGN AND IMPLEMENTATION OF A 2-DIMENSIONAL VIBRATION ABSORBER ON A PRE-HEATER TOWER AT A CEMENT FACTORY

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Abstract

This paper summarizes the work performed on a pre-heater tower at a cement factory to reduce the existing high-level resonance vibrations. An important feature of the problem was that the tower vibration was of elliptical shape, rather being along a line. Various simulations were performed based on a verified finite element (FE) model of the tower so as to understand the nature of the problem as well as to infer the associated dynamic loads. As an optimal solution of the problem it was decided to use a damped dynamic vibration absorber which would act on a plane at the top platform of the tower to overcome the excessive vibrations. A 2-D damped dynamic vibration absorber, a distinct feature of this work, was designed and the optimum parameters of the absorber were determined. An adjustable frictional damping device was also designed to produce the required damping in the form of dry friction. After the installation and tuning of a low cost 2D-vibration absorber, the measured results indicated an order of magnitude reduction in the tower vibrations. This made it possible to increase the nominal production rate while keeping the vibrations at acceptable levels.

INTRODUCTION

This investigation was initiated due to excessive vibrations of a pre-heater tower at a cement factory (CIMSA) in Mersin, Turkey. According to the information provided to the authors of this paper, the management of the factory had decided to increase the cement production rate of a pre-heater tower. Following this decision, a series of modifications had been made to the system, heavier cyclones were installed at higher platforms as well as strengthening of the structural components, i.e., adding further load carrying elements especially to the columns of the tower. After these modifications the whole tower had started to vibrate excessively at production rates far below the target level. This unexpected tower vibration had caused considerable concern about the structural integrity of the pre-heater tower, especially under unfavorable weather conditions. Furthermore, the cement production rate could not have been increased to the target rate so as to avoid further increases in vibration levels. This paper describes the steps involved during the solution of this vibration problem.

INITIAL MEASUREMENTS AND A THEORETICAL MODEL

Initial Measurements and Observations

The pre-heater tower shown in Fig.1a is made of steel with 7 platforms, 57 meter high with a total mass of about 1490 tons. The initial vibration measurements of the tower (using accelerometers, charge amplifiers, spectrum analyzer and an oscilloscope) were made in East and North directions at various locations in all platforms at various production rates in an attempt to quantify the level of vibration and also to identify the problem. A typical displacement spectrum in rms, corresponding to the top platform is presented in Fig.1b. The response levels indicated a coupled vibration in perpendicular directions, the time signals in individual directions being almost a sine wave as illustrated in Fig.2. As can be seen from Fig.3, the vibration amplitudes exhibited some variations from measurement to measurement under the same operating conditions. Following this preliminary investigation, the observations about the tower vibration were as follows:

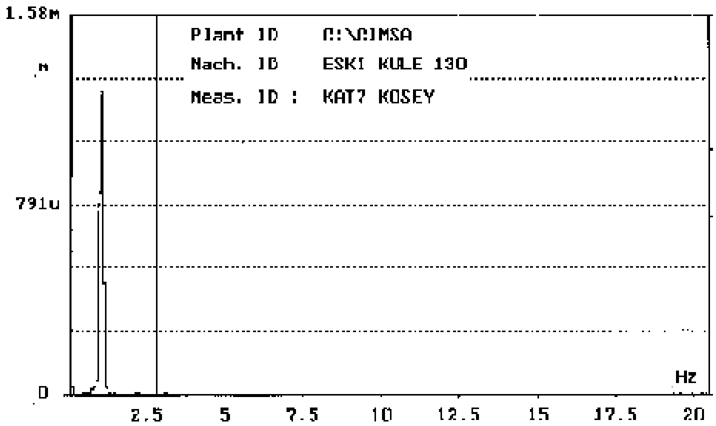
- The tower was vibrating at 1.04 Hz, irrespective of the production rate.
- The response signal was almost a pure sine wave, implying a typical resonance behavior.
- The increase in production rate caused sharp increases in vibration levels.
- The trajectory of the tower vibration was of elliptical shape, the minor axis of which being about 75% of the major axis. At 130 tons/h production rate, the peak-to-peak maximum vibration amplitude (the major axis of this trajectory) was, on average, 3.9 mm.

The excitation mechanism causing such vibration was unknown at the beginning as there was no rotating equipment on the tower. However, after some preliminary investigations, the excitation mechanism was identified as time-varying unbalance of rotating mixture within the dust separating cyclones. Another observation was that the frequency of the tower oscillations did not show any sign of change as the production rate was varied. This led to the belief that the tower was responding predominantly at 1.04 Hz which corresponds to one (or two) of its natural frequencies in bending. It was not possible to conduct vibration tests under non-operating condition for system identification purposes, as it was not possible to stop the production.

Theoretical Model for the Tower

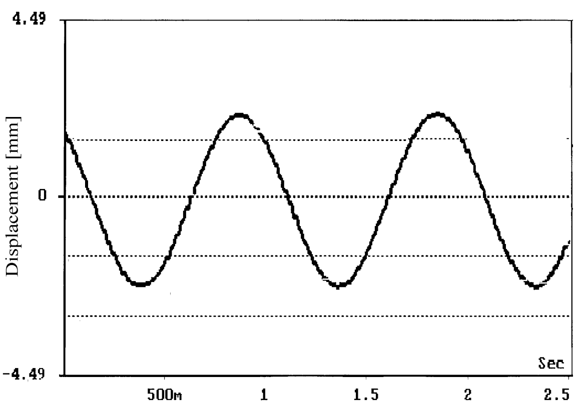
A finite element (FE) model for the pre-heater tower was developed using an in-house FE program and this model was used for several purposes which include: (i) performing simulations so as to gain in-depth understanding of the existing problem, (ii) judging the feasibility of several options for the solution (iii) optimizing the solution.

a)



b)

Fig.1 The pre-heater tower and a typical vibration spectrum in rms on the top platform. (North-South, Capacity 130 tons/hour)



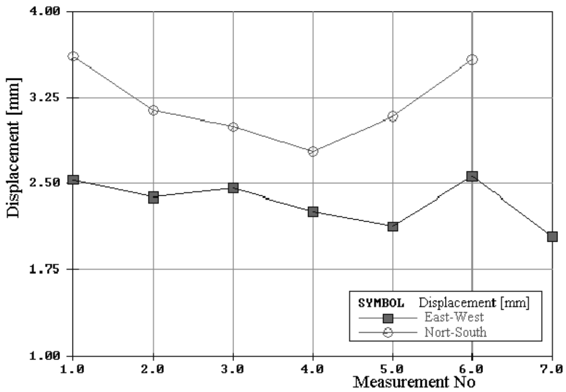
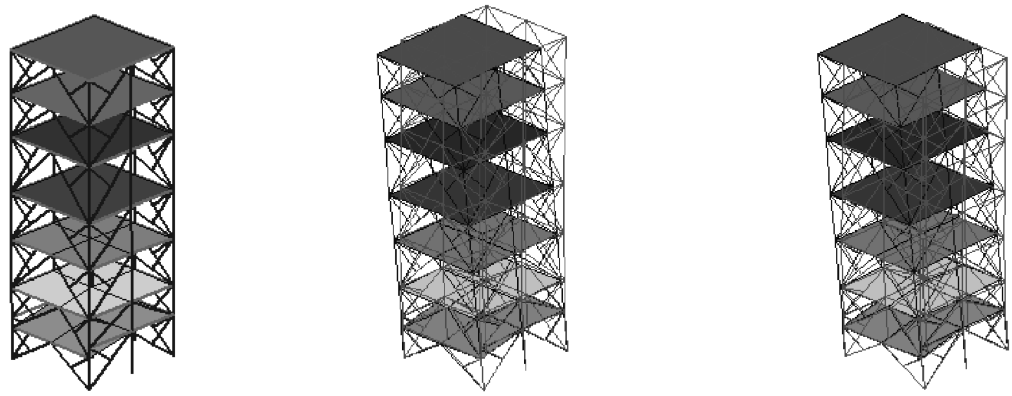


Fig.2 Time signal. Fig 3 Repeated measurements in perpendicular directions. (Production rate: 130 tons/h)

The FE model shown in Fig.4a consisted of mainly beam and shell elements representing the load carrying structural members. Lumped mass elements were also used to represent inertia properties of those components which are not designed to carry significant loads. Some minor modifications were made to the FE model to adjust the mass of the tower to the value (1490 tons) given in the technical specifications. The natural frequencies and mode shapes were predicted using the FE model. As expected, the first two modes were that of bending type with very close natural frequencies (1% difference between the two). As expected, the predicted first two natural frequencies correspond to first bending modes in South-North and East-West directions as illustrated in Fig.4. A few other modes, not illustrated here, are: 1^{st} torsion at 1.87 Hz, 2^{nd} bending modes at 3.46 and 3.53 Hz and, 2^{nd} torsion at 5.46 Hz.

The theoretical model allowed us to perform various simulations to reproduce the vibration pattern observed in practice. The mode shapes were visualized via animation and compared to the observed pattern. The forcing due to rotating air-dust mixture within the cyclone was simulated by a rotating force on a horizontal plane at the top platform of the tower. The predicted vibration pattern was almost identical to the observed motion, confirming that such an unbalanced rotating force was the most likely cause of the excessive vibrations.

Further analyses were performed to predict the magnitude of an equivalent rotating force that would reproduce the measured vibration amplitudes. It must be stated, however, that a representative damping value (1.5% structural damping) had to be assumed since it was not possible to measure the modal damping values. It is likely, however, that the assumed structural damping is somewhat an overestimate of the real value for the steel construction tower, but this was to ensure that the predictions would be on the conservative side.



a) FE model b) First bending mode (1.03 Hz) c) Second bending mode (1.05 Hz)
Fig.4 FE model for the pre-heater tower.

OPTIONS FOR OVERCOMING THE PROBLEM

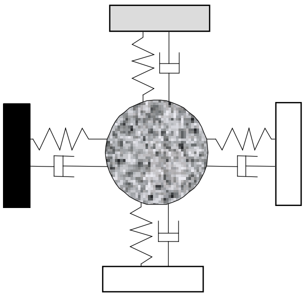
Several options were studied in order to reduce the tower vibration amplitudes to an acceptable level. A few options considered for the solution of the problem are summarized below:

i) Reinforcement of the Tower. If implemented properly, in such a way as to move the natural frequencies away from the forcing frequencies, this approach could have solved the problem. However, considering the scale of the tower, this option was considered very costly and not pursued any further.

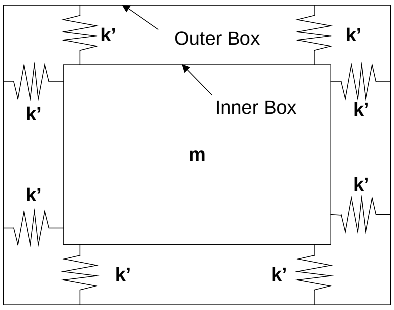
II) Providing Additional Damping. Providing additional damping using special damping devices was considered as an option. However, adding purpose-built damping elements at appropriate locations of the tower was found to be costly too. Designing a special device utilizing dry friction and installing this device on the top platform of the tower was also examined. However, velocities being too small did not make this an attractive option either.

III) Adding a Vibration Absorber With or Without Damping. In its simplest form, the well-known vibration absorber is essentially a spring-mass system tuned to a specific frequency, which is attached to another mass or system to reduce the vibration levels of the main body around the tuned frequency [1-2]. Vibration absorber concept is one of the most extensively studied subjects [3-7]. The work of Korenev and Reznikov [8] is a good example illustrating a wide range of applications of this concept, including the use of such devices in towers and buildings.

The tower vibration in our problem was a good candidate for the application of such a device, although a few complications needed to be resolved. The first issue was to decide whether to use an undamped or a damped absorber for this particular application. As the excitation spectrum was unknown, there was a possibility that with an undamped vibration absorber excessive vibrations could be shifted to newly created natural frequencies of the tower-absorber assembly. To be on the safe side, it was decided to use a vibration absorber with damping capability. The second issue was to decide on the number of vibration absorbers and how to construct them. After extensive simulations and analyses as well as cost considerations, it was finally decided to use a single vibration absorber capable of operating in 2D on the top platform plane of the tower as schematically illustrated in Fig.5a. The physical realisation of the 2D-vibration observer was to use two 'boxes' as shown in Fig.5b, the outer box to be fixed to the top platform of the tower, while the inner box, representing the absorber mass, to be suspended by four cables and connected to the outer box using springs.



a)



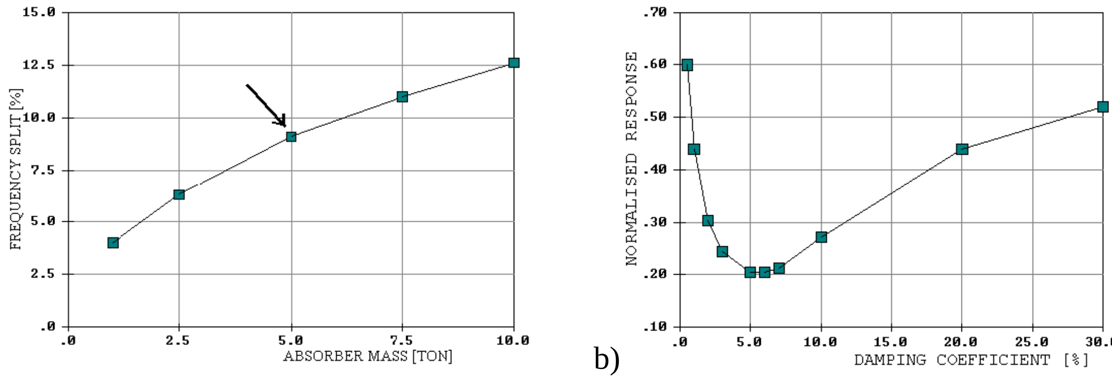
b)

Fig. 5 a) Schematic representation of the 2D-vibration absorber, b) Physical realisation of the 2D-vibration absorber (damping elements are not shown for clarity)

ANALYSIS OF TOWER VIBRATION WITH A 2D-VIBRATION ABSORBER

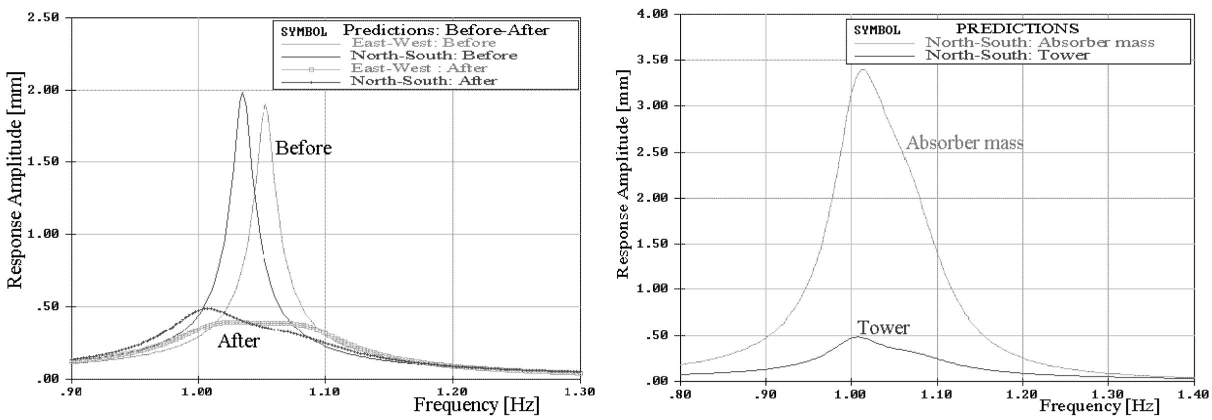
The physical parameters of a 2D damper that would result in sufficient reduction of vibration levels with minimum absorber mass were sought. The main criteria for determining the absorber mass was to obtain a sufficient frequency split related to the first bending modes of the tower. This was to ensure the effectiveness of vibration absorber within a narrow frequency range where excessive tower vibrations were observed. The analysis required at this stage was to obtain a relationship between the frequency split and the absorber mass. A structural modification software based on a method presented in reference [9] was used to avoid reanalysis of the FE model in a repetitive fashion. The relationship between the natural frequency split for the first bending modes and the absorber mass, as presented in Fig.6a, suggested that an absorber mass of 5 tons would cause about 9% frequency split. An absorber with 5 tons mass (0.4% of the tower mass) was considered as a minimum for a satisfactory result. Another important design parameter for the vibration absorber was to determine its damping properties to ensure dampening of vibrations at newly created modes. The optimum damping properties of the absorber was determined by minimising the resonant response levels of the tower corresponding to new modes of the tower-absorber assembly as shown in Fig.6b.

The rest of the predictions were aimed at estimating the level of vibration reduction when the 2D-vibration absorber was installed. This estimation was based on the worst scenarios; assuming that (i) the tower would be excited at new modes as strongly as before, (ii) minimum of 5 tons absorber would be used, and (iii) an overestimated structural damping value (1.5%) existed. The predicted forced response levels of the tower with and without the 2D-vibration absorber are presented in Fig.7a. It is seen that, under the most unfavorable conditions, the tower vibrations will be reduced to about 25% of the initial levels in both directions. Also, the maximum peak-to-peak response level of the absorber mass is predicted as 7 mm, see Fig.7b.



a) b)

Fig. 6 a) Determination of absorber mass as a function of frequency split.
b) Determination of the optimum absorber damping coefficient.



a) b)

Fig.7 a) Predicted response amplitudes (half of peak-to-peak) of a) the tower with and without 2D-vibration absorber and, b) the tower and the absorber mass in North-South direction.

INSTALLATION OF THE ABSORBER AND THE FINAL MEASUREMENTS

Having satisfactory results from the theoretical predictions, a 2D-vibration absorber shown in Fig.5b was manufactured and eight springs with appropriate flexibilities were installed between the inner and outer boxes. Four cables suspended the absorber mass. Adjustable friction dampers capable of operating in two-dimensions were designed and manufactured. The overall assembly was installed on the top platform of the tower as shown in the pictures in Fig.8 where various details of the final assembly can be seen.

Tuning operation was performed in two stages. First, the absorber mass was gradually increased to the target value. Then, the friction dampers were adjusted to their optimum values. As planned, the final absorber mass, 6870 kg, was more than the value used in the predictions. Furthermore, a lower level of additional damping than anticipated was sufficient for optimum absorber performance. As a result, much better performance of the vibration absorber than what has been predicted based on worst case scenarios was achieved. The tower vibrations with and without the 2D-vibration absorber are compared in Fig.9a. On average, the tower vibrations were reduced to about 10% of the initial levels. The displacements of the absorber mass were also in line with the predictions, Fig.9b. The amount of response reduction can also be seen by comparing the vibration spectrums of the tower in Fig.10.

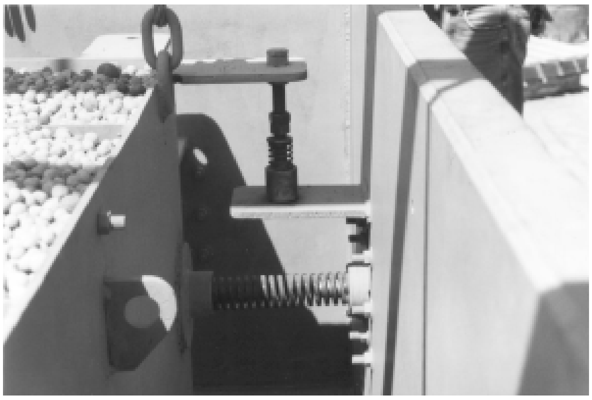
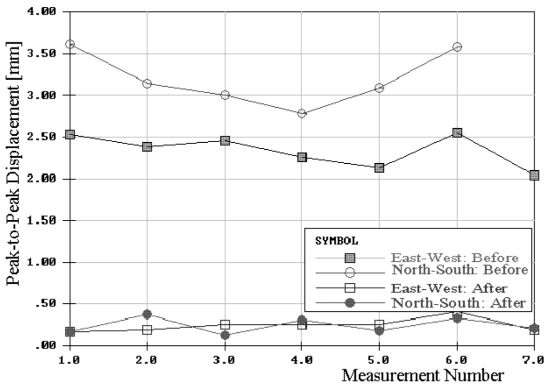
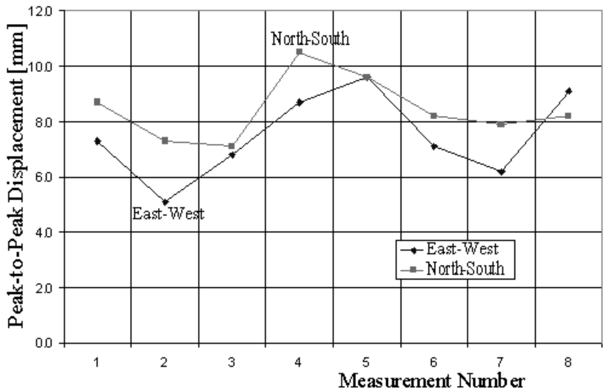
a)  b) 

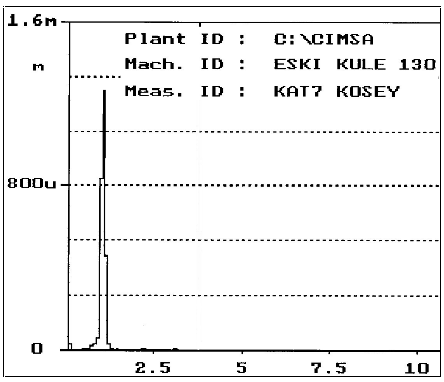
Fig.8. a) Overall view of the 2D-vibration absorber, b) Spring and friction damper connections.

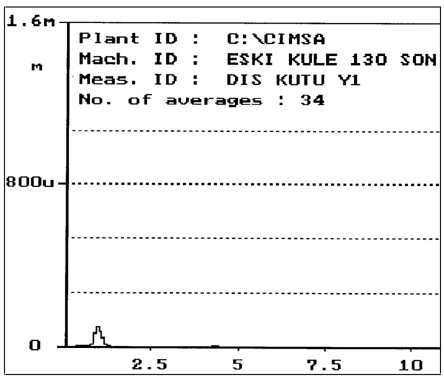




a) b)

Fig.9 a) Comparison of tower vibrations with and without 2D-vibration absorber, b) Peak-to-peak displacement of the absorber mass in perpendicular directions.





a) Before b) After

Fig.10 Comparison of measured vibration spectrums [in rms] on the top platform in North-South direction: a) before and b) after the installation of 2D-vibration absorber (Capacity 130 tons/hour)

CONCLUDING REMARKS

In this work, excessive vibrations of a pre-heater tower of a cement factory have been reduced to acceptable levels successfully. This has been achieved by using a low cost and very effective 2D-damped vibration absorber system functioning in two directions simultaneously. A 2D-vibration absorber was designed with the aid of a verified finite element model of the tower, which was effective in reducing the vibration levels of the tower by an order of magnitude. Thus it was possible to increase the nominal production rate by 8% while keeping the vibrations at acceptable levels, similar to that of other towers operating without any problem. At the time of writing this paper, the 2D-vibration absorber has been functioning satisfactorily for the last 8 months. The final results were fully compatible with theoretical predictions. Further concluding remarks are: (i) 2D-damped vibration absorber is an effective way of overcoming 2D-vibration problems exhibiting a spectrum with a narrow band frequency content, and (ii) suspending the mass of the damped vibration absorber using cables seems to work well for achieving planar absorber motion for 2D applications of such devices.

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