Wind Tunnel Testing for Vibration Analysis of High Rise Building Due to Wind load

Matza Gusto Andika*, Fariduzzaman*, Yanto Daryanto*
* National Laboratory of Aerodynamics, Aero elastics, and Aero Acoustics Technology
BPPT, PUSPIPTEK, Serpong, Tangerang, INDONESIA

***Abstract*- The development of high-rise buildings should be followed by the development of technology related to the safety and comfort of building occupant. The Higher a building the earthquake forces was relatively smaller, on the other hand the higher a building, the wind speed is also increased. So it could be at a certain height, seismic forces that work on a high rise building does not become dominant compared to the effect of the wind. Wind load can induce vibration on high rise building which leads to occupant discomforts as well as fatigue of structural members and their linkages. Wind tunnel testing is a tool to assess vibration on high rise building due to wind load, where the major phenomenon is vortex induced vibration (VIV). In this research, vortex induced vibration occurs at 8.4 m/s wind speed in wind tunnel for first natural frequency. Besides VIV, there is other phenomenon occurs at the wind tunnel testing, that is lock-in phenomenon where it starts from 7.8 m/s up to 8.4 m/s with increasing amplitude, and decline afterwards until the next model natural frequency excited.**

***Index Terms*—Vibration, High Rise Building, Vortex induced vibration, Lock - in, Wind tunnel testing**

I. INTRODUCTION

Wind load on high rise building are very complex, because of many aspects can effects the phenomenon. For instance: shape of the building, terrain around the building, vortex shedding, pressure fluctuation, etc. Wind flow around the building causes the building to oscillate, along wind, cross wind direction, and torsion. Then, vibration on high rise building might reveals the occupant discomfort and fatigue in structural members and their linkage.

Isyumov suggested acceptance criteria for the limitation of wind-induced accelerations to ensure occupant comfort for return periods of both 1 and 10 years. The one year return period criterion specifies two ranges of peak acceleration, shown in Fig. 1 as shaded bands: 5–7 mg for residential buildings and 9–12 mg for office buildings. [1]

Wind tunnel testing is now common practice for design of high rise buildings. The objective of wind tunnel testing is to determine the wind-induced loads and building top floor accelerations with which occupant comfort can be assessed against international building vibration acceptability and occupant comfort criteria. Wind tunnel testing can produce reliable information for designers and minimized the initial capital costs, and more significantly avoiding expensive maintenance costs associated with malfunctions due to structural failure. This paper examines a wind tunnel testing for analyzing vortex induced vibration and lock-in phenomenon on squared shape high rise building which can cause discomfort for the occupant.

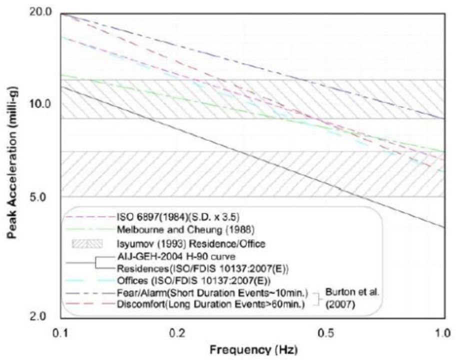

Figure 1. Comparison of occupant comfort serviceability criteria [1]

II. WIND LOAD ON HIGH RISE BUILDING

Wind load on high rise building classified on two types: along wind load and cross wind load. The phenomenon in the along wind load is buffeting. It is cause by fluctuating wind around the building. That is, when turbulence intensity is high or turbulence flow dominate the wind load. In high turbulence intensity, the structural response is relatively high magnitude but in random fluctuation. In low turbulence intensity, the structural response is relatively low magnitude. Only at certain wind speed or natural frequency of structure the oscillation magnitude is high.

Fig. 2 and 3 describe frequency spectrum response for structural in high turbulence intensity and low turbulence intensity.

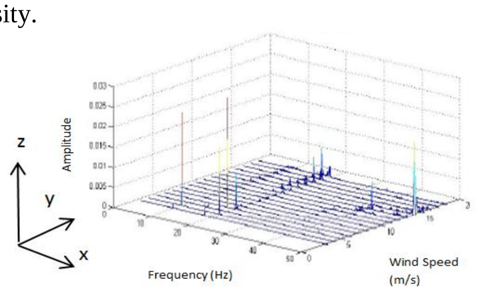

Figure 2. Frequency spectrum for high turbulence [2]

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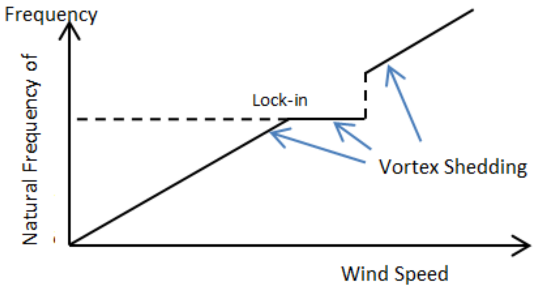

Figure 3. Frequency spectrum for low turbulence [2]

Vortex induced vibration is structural vibration induce phenomenon cause by vortex shedding around the building which its frequency is coincide with natural frequency of the structure. Another phenomenon in cross wind direction is lock-in, lock-in occur, not only in one critical wind velocity but also in several wind velocities. The occurrences show specific properties of a structure.

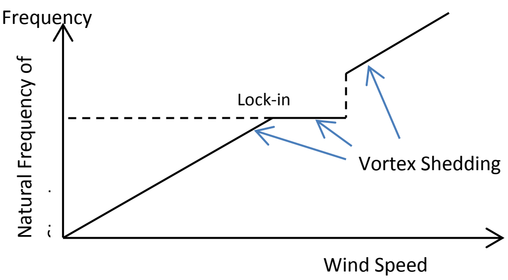

Figure 4. Lock-in phenomenon

The equation of motion for cross wind response can be written in the form [3] :

$$m\ddot{x} + c\dot{x} + kx = \frac{1}{2}\rho v^2 D C_{LS} \sin \omega_s t \quad (1)$$

$$\omega_s = 2\pi f_s \quad (2)$$

Where C_{LS} is aerodynamic coefficient and D is the characteristic length. It can be known that the cross wind response is depend on frequency vortex shedding (f_s). Vortex shedding frequency is related to Strouhal number, where Strouhal number can be written in the form

$$St = \frac{f_s D}{v} \quad (3)$$

or equation 3 can be written as

$$v = \left(\frac{D}{S_t}\right) f_s \quad (4)$$

III. Vortex Shedding Around the Building

Wind flow over the surface of building will have pressure changes. Negative pressure which go to the upstream region will disturb boundary layer at the surface body. Disturbed flow generates turbulence flow around the surface, which have fluctuating velocity. Turbulence flow have many type of eddies depends on eddies size. Energy cascade theory by Richardson said that turbulence is consist of many size of eddies, where occur energy transfer from large size eddies to small size eddies and to the other smallest eddies until the smallest eddies dissipate energy to thermal energy [4].

Some point in turbulence flow is call separation point where eddies or vortex start release from surface, that phenomenon commonly call vortex shedding. Vortex shedding have some frequency depend on wind velocity, wind velocity direction, and the shape of building. When the frequency of vortex coincides with natural frequency of the building then the building will vibrate with amplitude higher than before.

The originally parallel upwind streamlines are displaced on either side of the building, Fig. 5 This results in spiral vortices being shed periodically from the sides into the downstream flow of wind, called the wake. When the vortices are shed, that is break away from the surface of the building, an impulse is applied in the transverse direction. [5] Fig. 5 also shows the phenomenon when the vortex shedding on building occur and make building vibrate with some deflection.

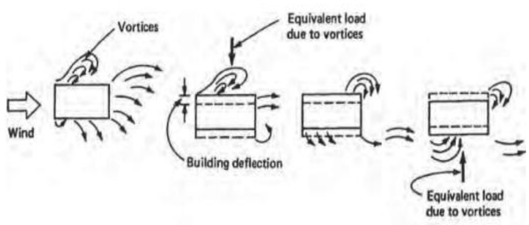

Figure 5. Vortex shedding phenomenon [5]

The vortex shedding frequency around the building follows the Strouhal relationship, and the building vibrates with small amplitude. When the flow velocity is sufficiently high, the vortex shedding frequency comes close to the first natural frequency, ω1, and locks on to this. Large amplitude vibrations in mode 1 will then quickly develop.

IV. Wind Tunnel Experiment

Experiment for identifying model structural response as results of dynamic wind load on building is wind tunnel test. The wind tunnel is LIWET (LAGG industrial and wind engineering tunnel), operates by National Laboratory of Aerodynamics, Aero elastics, and Aero Acoustics – BPPT. Indonesian agency for Assessment and Application of Technology. LIWET has test section of 1.5m height and 2 m width and maximum wind speed is 20 m/s. The rule of wind tunnel testing for vibration on high rise building that all wind force and structural response can be scaled down in some proportion to wind tunnel condition, structural dynamic of building, and structural geometry. The strouhal number is the non-dimensional function and important similarity between real building and wind tunnel model building. The strouhal number both the real building and wind tunnel model must be in the same number, then wind tunnel model should be design at certain natural frequency and mode shape [6].

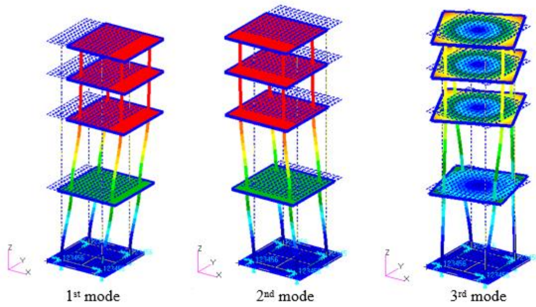

Figure 6. Mode shape of wind tunnel model

At this research the model first natural frequency is 4.1 Hz (first bending mode shape) and model third natural frequency is 6.1 Hz (first torsion mode shape). The building model for the experiment is squared building of 200 m height and scaled down to 1:300 scale. The model is a lumped mass with four mass and stiffness, as shown in Fig. 6 and 7.

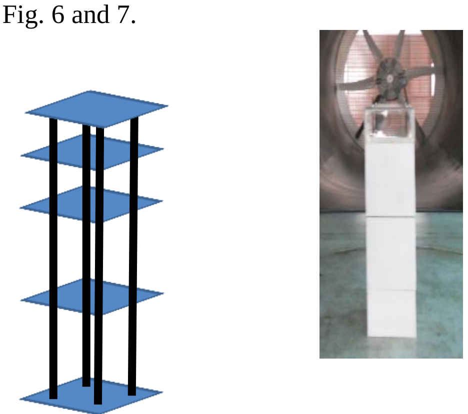

Figure 7. Skeleton structure of model with dimensions and building model in wind tunnel

Vibration response measure with accelerometer at the top of the model in cross and along wind direction. Figure 8 shows schematic data acquisition during wind tunnel testing.

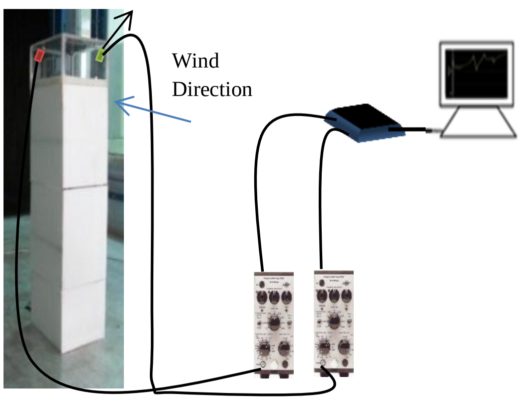

Figure 8. Schematic of vibration measurement in wind tunnel

V. Analysis of Vibration Induced by Wind Load

Vibration phenomenon on high rise building of wind load origin can be observed from vibration measurement on the building model in the wind tunnel. Wind response direction divided to across wind and along wind load direction. Along wind response refer to drag forces, and transverse wind is the term used to describe crosswind. The crosswind response causing motion in a plane perpendicular to the direction of wind typically dominates over the along-wind response for tall buildings.

From Fig. 9 and 10 shows that the amplitude of crosswind response higher than along wind response both time domain and frequency domain analysis. So the crosswind effect at the high rise building is more significant to make occupant discomfort than along wind. Therefore, further research is needed on analyzing crosswind phenomenon at high rise building.

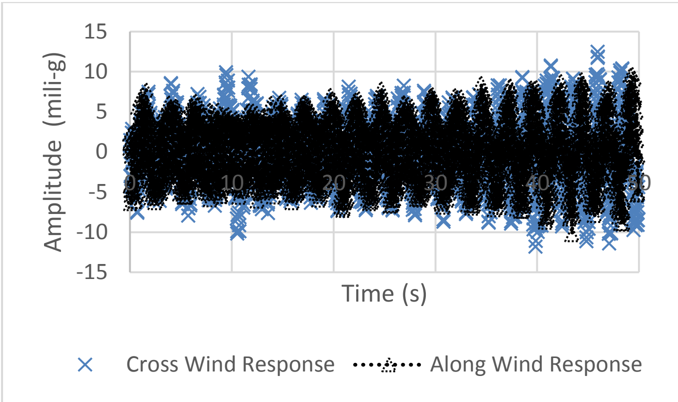

Figure 9. Time domain of building response due to wind load

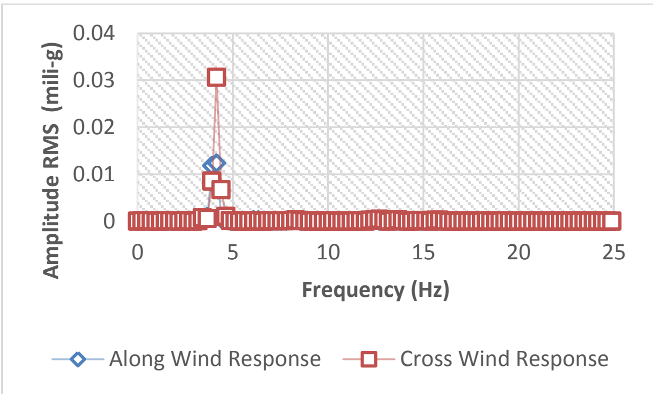

Figure 10. Frequency domain of building response due to wind load

The most common source of crosswind response is the vortex shedding which associate with dynamic characteristic of building. VIV occurred when the vortex shedding coincide with the building natural frequency. VIV can be observed from structure vibration response pattern under wind load, where wind speed is gradually increased.

When critical wind speed response occurs, the oscillation amplitude will suddenly increase higher than before. The critical wind speed is the speed when the VIV occurred. Lock-in occurs not only at one wind speed but also at some region wind speed. In the lock phenomenon the vortex shedding frequency is constant not a linear function of wind velocity as suggested by Eq. 3.

We can see lock in phenomenon in waterfall plot at figure 11 and 12, when the wind speed at 7.8 m/s the first natural frequency of structure (4.1 Hz) induced and the peak amplitude at 8.4 m/s at the same frequency and the amplitude decrease at 8.9 m/s. Vortex induced vibration occur in lock-in region when the vibration amplitude is higher than other wind speed at lock-in region.

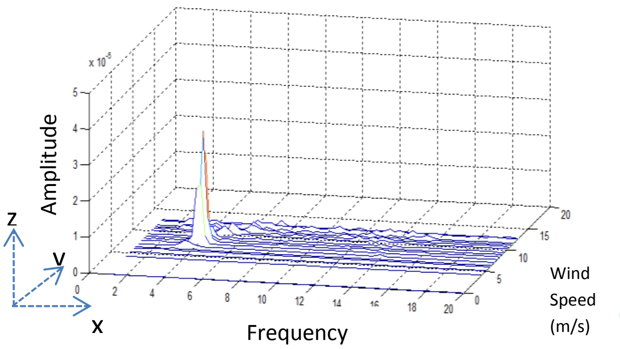

Figure 11. Waterfall plot vibration response at difference wind speed

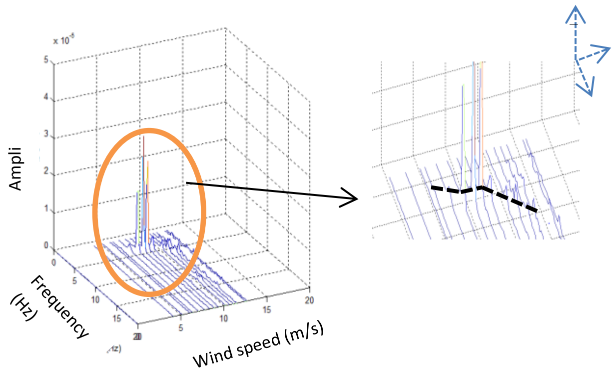

Figure 12. Zoom waterfall plot

The other important things for vibration induced by wind which we should know is Strouhal number. From equation 4 we know that the wind speed (v) and Strouhal frequency (f_{st}) have linear relation which gradient, that is D divided by Strouhal number. Therefor when the Strouhal frequency equal to bending model natural frequency (4.1 Hz) at wind speed 8.4 m/s and Strouhal frequency equal to torsion model natural frequency (6.1 Hz) at wind speed 11.5 m/s then the gradient (D divided by Strouhal number) is: 1.587, and the Strouhal number (S_t) became 0.126.The strouhal number which obtained in this study is match with the experiment from Tamura and Miyagi (1999) where conduct at Tokyo Institute of Technology wind tunnel for square cylinder.

VI. Conclusion

Vibration induced on high rise building due to wind load can occur of many causes. The direction of wind response on high rise building divided to across wind and along wind load direction. The vibration amplitude of crosswind response is higher than along wind response. The most common phenomenon of crosswind response is the vortex induced vibration. Vortex shedding can induce vibration if the frequency of the vortex shedding coincides with natural frequency of high rise building. Vortex induced vibration phenomenon on high rise building can be analyze using wind tunnel testing as aero elastics lumped mass building model.

With increasing wind speed in suitable steps, record the building model vibration response, and make waterfall plot, we can identify the occurrence of lock-in phenomenon and vortex induced vibration. The waterfall plot contains frequency response, response amplitude in frequency domain, and wind velocity. From the wind tunnel test result the strouhal number can be identified at 0.126 which match to the past research.

From this research and wind tunnel testing we can also produce aero elastic parameters which is required by building designer and developer which can assess occupant comfort serviceability base on the criteria such us critical wind speed when VIV occur.

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Matza Gusto Andika was born in Jakarta, Indonesia on July 6th 1985. Matza is a Group Leaader at Industrial and Wind Engineering research group in National Laboratory of Aerodynamics, Aero elastics, and Aero Acoustics Indonesia. He was completed a master's degree on Aeronautics and Astronautics Engineering at Bandung Institute of Technology. He was join Global Center of Excellence Short Term Fellowship at Tokyo Wind Engineering Research Centerto study about Reduced Wind Induced Vibration of Tall Building. He was publishing some paper about wind load on long span bridge and high rise buiding.