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

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ABSTRACT
Wind load can induce vibration on high rise building which can cause discomfort to occupants and fatigue in structural members and connections caused by fluctuating wind loads. Vibration on high rise building due to wind load can cause by vortex shedding around the building. Wind tunnel testing is a way to asses vibration on high rise building because of wind load. With doing wind tunnel testing we can analyze vibration cause by vortex shedding which call vortex induced vibration. In this research vortex induced vibration occur at wind speed 8.4 m/s in wind tunnel which excited high rise building dynamic model with 4.1 Hz first natural frequency. The other phenomenon which can be analyze in this research is lock-in phenomenon, lock-in phenomenon is start at 7.8 m/s wind tunnel speed which induce model natural frequency structure at 4.1 Hz, when the wind speed is up to 8.4 m/s the frequency still at 4.1 Hz but the vibration amplitude is rising, and when the wind speed is up to 8.9 m/s the vibration amplitude is decline at the same frequency at 4.1 Hz, when the speed is more than 8.9 m/s the frequency is more than 4.1 Hz and the amplitude decline until the next model natural frequency excited by vortex shedding frequency.

Keyword: Vibration, High Rise Building, Vortex induced vibration, Lock-in, wind tunnel testing

1. INTRODUCTION
Wind load on high rise building are very complex, because of many aspect can effect wind load as if shape of the building, terrain around the building, vortex shedding, pressure fluctuation, etc. Wind flow around the building can make building oscillation in along wind, cross wind direction, and torsion. Vibration on high rise building can cause discomfort to occupants and fatigue in structural members and connections caused due to fluctuating wind loads. In the Figure 1. is describe vibration comfort level from many standard.

![Figure 1. Comparison of occupant comfort serviceability criteria](image-url)
Wind tunnel testing is the common method to knowing wind loading phenomenon on high rise building, this paper examine wind tunnel testing for analyzing vortex induced vibration and lock-in phenomenon on squared shape high rise building.

2. WIND LOAD ON HIGH RISE BUILDING

Wind load on high rise building classified for two type based on the direction of the response, that is along wind load and cross wind load. The phenomenon in the along wind load is buffeting, buffeting is vibration on high rise building in along wind response cause by fluctuating wind around the building. Buffeting phenomenon occur when turbulence intensity is high so turbulence flow dominate in wind load. If we measure structural response for high turbulence intensity we can get random fluctuation wind load, with low turbulence intensity we can see more frequency response more clearly. Figure 2 and 3 describe frequency spectrum response for structural in high turbulence intensity and low turbulence intensity. The phenomenon in cross wind load is vortex induced vibration and lock-in.

Figure 2. Frequency spectrum for high turbulence

Vortex induced vibration is structural vibration induce phenomenon cause by vortex shedding around the building which have frequency coincide with natural frequency of the structure. Another phenomenon in cross wind direction is lock-in, lock-in occur not only in the one wind velocity but also in some region wind velocity. Vortex induced vibration occur in the lock-in phenomenon region when the vibration amplitude is high then the other, so the wind velocity when vortex induced vibration occur it is call critical wind speed.

Figure 3. Frequency spectrum for low turbulence

Figure 4. Lock-in phenomenon
The equation of motion for cross wind response can be written in the form \[3\]:

\[ m \ddot{x} + c \dot{x} + k x = \frac{1}{2} \rho v^2 D C_{LS} \sin \omega_s t \]  

(1)

\[ \omega_s = 2\pi f_s \]  

(2)

From that equation where \( C_{LS} \) is aerodynamic coefficient and \( D \) is the characteristic length we can know 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

\[ St = \frac{f_s D}{v} \]  

(3)

or equation 3 can be written as

\[ v = \left( \frac{D}{St} \right) f_s \]  

(4)

3. VORTEX SHEDDING AROUND THE BUILDING

Wind flow which disturbance by surface of the building will be have pressure change. Negative pressure which go to the upstream region will disturbed the boundary layer at the surface body. Disturbed flow can make turbulence flow around the surface, which have fluctuating velocity. Turbulence flow have many type of eddies depend on eddies size. Energy cascade theory by Richardson said that turbulence are 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 it 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 coincide with natural frequency of the building then the building will vibrate with amplitude more higher than before. Figure 5. describe when the vortex shedding on building occur and make building vibrate with some deflection.

![Figure 5. Vortex shedding phenomenon](image)

4. WIND TUNNEL EXPERIMENT

Experiment model design for knowing model structural response cause by dynamic wind load on building specially vortex induced vibration and lock-in phenomenon. Wind tunnel which use is LAGG industrial and wind engineering tunnel, that wind tunnel is a one of wind tunnel in aerogasdynamic and vibration laboratory under the agency for the assessment and application of technology Indonesia.
LAGG industrial and wind engineering tunnel have test section with height 1.5m and width 2m with maximum wind speed is 20 m/s and under construction for more high wind speed. Building model which used in experiment is the squared building with height 200m and use 1:300 scale in wind tunnel. Building model is modeled as a lumped mass with four mass and stiffness which describe in Figure 6.

![Figure 6. Skeleton structure of model with dimensions and building model in wind tunnel](image)

Vibration response measure with accelerometer on the top of the model in cross and along wind direction. Figure 7. Is the schematic of data acquisition for wind tunnel testing.

![Figure 7. Schematic of vibration measurement in wind tunnel](image)

5. **ANALYSIS OF VIBRATION INDUCED BY WIND LOAD**

Vibration phenomenon on high rise building due to wind load can be observed from vibration measurement on the building model in the wind tunnel. VIV can be observed from structure vibration response pattern when the building model structure under wind load which wind speed gradually increased. For critical wind speed response amplitude suddenly higher than before, the critical wind speed is the speed when the VIV occurred. Another vortex induced phenomenon is a lock-in, lock-in
occur not only at one wind speed but also at some region wind speed. In the lock in region the vortex shedding frequency is constant rather than being a linear function of wind velocity as suggested by Eq. 3. We can see lock in phenomenon in waterfall plot at figure 8 and 9, 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 8. Waterfall plot vibration response at difference wind speed](image1)

![Figure 9. Zoom waterfall plot](image2)

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 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:
Figure 10. linearity between Strouhal frequency \( f_{st} \) and wind speed \( v \)

We can get Strouhal number from:

\[
\frac{D}{S_t} = \left( \frac{V_2 - V_1}{f_{st, torsion} - f_{st, bending}} \right) = \frac{11.5 - 8.4}{6.1 - 4.1} = 1.587
\]

Dengan parameter \( D = 0.2 \text{m} \) maka, \( \frac{D}{S_t} = \frac{0.2}{S_t} = 1.587 \), \( S_t = 0.126 \)

6. CONCLUSION

Vibration induced on high rise building due to wind load can occur because of many causes, vortex shedding can induce vibration if the frequency of the vortex shedding coincide with natural frequency of high rise building. Vortex induced vibration phenomenon on high rise building can be analyze from wind tunnel testing with aeroelastics lumped mass building model. With increasing wind speed step by step and record building model vibration response and make waterfall plot which contain frequency response, response amplitude in frequency domain, and wind velocity we can analyze when the lock-in phenomenon and vortex induced vibration occur. When the lock-in phenomenon occur at some wind speed vibration amplitude began to high until the highest amplitude in lock-in region when VIV occur in the same frequency, after VIV occur vibration amplitude decrease gradually but still in the same frequency until at some wind speed when the frequency response is change from lock-in frequency.

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