Assessment of static aerodynamic stability bridge with computational and experimental method

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Abstract. The bridge is the connector between two separate places. In order to manufacture the bridge, it needs to be divided into segments. Each certain distance and each segment has a cross-sectional shape in the form of a deck. Long-span bridges require aerodynamic stability due to the wind blow whose speed is varied. In order to obtain a stable design of the bridge deck, there are two complementary methods, namely the method of computation and experimentation. This paper discusses the application of computational methods and experimental for a deck of long spans bridge. The results of the simulation and experiment are in the means of aerodynamic characteristics, i.e. curve of lift, drag and moments coefficient. Aerodynamic stability can be concluded from the results of these methods.

1. Introduction

The development of the automotive, train and the transportation system is increasingly required because of the needs of the community. Ground transportation is dominated by motor vehicles and trains growing the population of spacecraft. Thus, bustles of highway increase inevitably. Here the needs for management of transportation continue to be improved. For example, the construction mode of bus in Jakarta, known as the Trans Jakarta is one of the ways to decrease the number of vehicles on the street. Likewise, the development of Mass Rapid Transportations (MRT) and Light Rapid Transportations (LRT) is expected to provide solutions to the problems of congestion in the capital city of Indonesia.

Similarly, if the city's transportation needs the addition of mass transportation, certainly it also needs addition of roads and bridges. Through the means of transportation the results of regional products can be brought and distributed smoothly between the city and other islands. In order to speed up the distribution of goods and services as well as the development, building bridges is needed to connect the islands in Indonesia. Currently, Indonesia has had a long span of Surabaya-Madura bridge [1] connecting Java with Madura Island. With the existence of the Surabaya-Madura bridge, the bridge takes vehicles increasingly shortened because it can cross over without having to climb aboard. The development of the region is expected to be faster so that welfare will distribute evenly.

In designing the bridge the determination of the geometry of the bridge deck is required. Bridge decking geometry then is examined whether it has adequate stability aerodynamically given the bridge deck would be strung together as a long stretch of being elastic. This paper discusses the necessity of the study of the geometry of the two-dimensional bridge deck which was simulated by Computational Fluid Dynamics software (CFD) [2] and experimentally in a wind tunnel [3][4].
2. Computational and experimental method

Examination of the stability of bridge deck geometry numerically is the first step of this study. Once the shape of the deck was selected and determined based on the results of the simulation, it was then followed by a two-dimensional model test in a wind tunnel. The test in the wind tunnel was used as a basis to confirm whether the choice of the geometry of the deck already meets the criteria of aerodynamics stability. In this chapter the method of simulation and experimental use are outlined.

2.1. Computational method

The geometry of the long span bridge deck is very essential to be examined to get a stable geometry. In this chapter, the author used the CFD simulation method to simulate the flow around the geometry of the bridge deck. CFD simulation of the flow around the deck was completed with the Navier-Stokes equations. Numerical simulation was conducted based on some assumptions below:

A. The bulk fluid is air with properties as follows:
   - Temperature: 298.15 K
   - Viscosity: 1,789x10^-5 kg/m. s
   - Density: 1,225 kg/m³

B. Flow:
   - Turbulent
   - Steady
   - Compressible

Based on the above assumptions, the equations solved include:

Continuity equation:

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0$$  \hfill (1)

Reynolds Average Navier-Stokes equation:

$$\frac{\partial}{\partial x_j}(\rho u_j u_j) = -\frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial u_i}{\partial x_i} + \frac{\partial u_j}{\partial x_j} - \frac{2}{3} \delta_{ij} \frac{\partial u_l}{\partial x_l} \right) \right] + \frac{\partial}{\partial x_j} \left( \rho u_i u_j - \rho u_i' u_j' \right)$$  \hfill (2)

Here, the $u_i$ is the velocity in the direction in i, and $u_i'$ is the value of fluctuation. Turbulence modeling was done using k-ε turbulence model is realizable. The model reported relatively better predictions for the flow is interrupted [5] as the flow around the deck of the bridge. Interactions between fluctuations of speed known as Reynolds stress, calculated based on the assumption that the Boussinesq equation like Reynolds stress is proportional to the velocity gradient viscous with the comparison of what called as the viscosity of turbulent $\mu_t$. This turbulent viscosity calculated by how to solve the equations of turbulent kinetic energy $k$, and the speed of the dissipation of $\epsilon$ below by using the equation of turbulent kinetic energy:

$$\frac{\partial}{\partial x_j}(\rho k u_j) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \epsilon - Y_M + S_k$$  \hfill (3)

The capacity equation of dissipation of turbulent kinetic energy is:

$$\frac{\partial}{\partial x_j}(\rho \epsilon u_j) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_j} \right] + \rho C_{1\epsilon} \epsilon \frac{\epsilon}{k + \sqrt{\nu \epsilon}} + \rho C_{2\epsilon} \frac{\epsilon^2}{k} + C_{3\epsilon} \frac{\epsilon}{k} + C_{4\epsilon} G_b + S_\epsilon$$  \hfill (4)
Furthermore, equation (1) through (4) sought it's numerically discretized the physical space into the computing space. In each grid point, count and size distribution obtained velocity, pressure, and then be calculated coefficients of forces and moments aerodynamics. Moreover, with regard to model turbulent flow can find in the Fluent manual (2006) [6]. CFD simulation of flow condition around the bridge on a wind speed of 30 m/s with the variation of angle of attack $\alpha$: $-10^\circ, -8^\circ, -6^\circ, -4^\circ, 2^\circ, 0^\circ, 2^\circ, 4^\circ, 6^\circ, 8^\circ, 10^\circ$.

Taking one of the cross section girder bridge decks is an important part to obtain the best simulation flow. Modeling of the bridge deck cross-section done by GAMBIT (Geometry and Mesh Building Intelligent Toolkit) software. Figure 1 shows a cross-sectional girder bridge 2-D.

![Figure 1. Cross-sectional girder bridge 2-D.](image)

Simulation of the flow around the bridge deck 2-D performed with attack angle variation, the variation amount of the mesh, and the variation of the boundary conditions. The shape of the domain used in the simulation as shown in figure 2, the domain of computing take a distance of 15 times the length of the stretch (B) upstream, top, and bottom, while the downstream direction at a distance 31 times the length of the stretch. Large computational domain adopted from the results of studies conducted parameters of Bruno and Khris [7]. The long stretch of bridge model is 0.214 m and 0.042 m high. The computational domain is then discretizing by creating the lattice into a mesh. As shown in figure 3, mesh arranged so that is smoothly in areas closer to the wall where the flow quantities have a very diverse gradient.

The form of mesh in this paper uses two forms of structure mesh (map) and unstructured (pave). Figure 3 shows the surface areas of the deck of the bridge using shape mesh structure as for the next surface using unstructured mesh.

![Figure 2. Domain computation according to Bruno and Krish [7.](image)
2.2. Experimental method

First, before the testing is going to do, we should prepare the model of geometry that is already determined. The design of the model of two-dimensional (2-D) using the software CATIA. The result of the designed model is shown in figure 4. 2-D models are equipped with holes to measure the pressure of the upper and lower surface of the model [8]. Bridge sectional model of the static bridge is a replica of the bridge deck structure of the center with the reduction of the scale of 1:40. Where the equality rules that must be met merely stated aerodynamic equivalence of equality form the geometry of the design of the structure created by the designer. In the sectional static models, rules of equality used are equal geometry, thus the material density is not too important models for the consideration of the design and manufacture of models. Equality geometry is sensitive in the area around the pressure tab. Just need special attention to the structural components which, if reduced will give Reynolds leather than 100. On the structure of the model, a very small value of the CD will be different between models with the prototype. Based on the calculation rules of equality, to a scale of 1:40, the size of the smallest model of railing in-let is 0.3 mm. For that, the structure sometimes-sectional models or cable railing should not always follow the rules of reduction of the scale.

Once the designs completed the model then create a test model using a CNC machine. The completed 2-D model is ready to install in a wind tunnel test section. Figure 5 shows the model 2-D mounted in a wind tunnel test section. In some cases 3-D model testing we should simulate Atmospheric Boundary Layer in order to obtain appropriate experimental data result [9][10][11].
3. Results and discussions

3.1. The coefficient of lift, drag and moment of aerodynamics

The coefficient of lift, drag and moment of aerodynamics [12] define as follows:

\[ C_L = \frac{F_L}{\frac{1}{2} \rho U_0^2 B} \]  
\[ C_D = \frac{F_D}{\frac{1}{2} \rho U_0^2 B} \]  
\[ C_M = \frac{F_M}{\frac{1}{2} \rho U_0^2 B} \]

The direction of force and moment are shown in figure 6.

3.2. Simulation and experimental result of lift, drag and moment coefficient

The results of simulation data and experiment data pattern graphs with a wind speed of 30 m/s show in figure 7, figure 8 and figure 9.
Figure 7 shows the magnitude of the coefficient of lift versus the angle of attack. The X-axis shows the value of the angle of attack while the Y-axis is the coefficient of lift.

![Graph showing the coefficient of lift versus the angle of attack.](image)

**Figure 7.** The comparison of lift coefficient.

Figure 7 shows that the wind conditions at the angle of attack $-10^0$, indicating a negative lift coefficient means that the wind will increase the burden to the bottom (in the direction of heavy loads) and gradually became positive lift on the angle of attack $> 0^0$. The anomaly for simulation result is the location of the stall that occurs at an angle of attack around $-4^0$ means the nonlinearity in aerodynamic occurs.

![Graph showing the comparison of lift coefficient between simulation result and wind tunnel test.](image)

Figure 8 shows aerodynamic drag simulation and experiment results, where the minimum drag occurs at an angle of $0^0$. The magnitude of the induced drag or drag due to lift a relatively small so drag coefficient curve so far slightly small changed.

Static aerodynamic stability can be shown in figure 9, which shows characteristics of the aerodynamic stability as represent by moment coefficients and their changes to the angle of attack. From the graph simulation results, show that moment coefficient increases as well as an increasing angle of attack. In addition, the angle of attack between $4^0$ to $10^0$ will be inherently stable.

![Graph showing the comparison of drag coefficient between simulation result and wind tunnel test.](image)
4. Conclusions

Static aerodynamic can be presented by curve moment coefficient. Both simulation and experiment result shown the good agreement. The stability static aerodynamics find out if $\frac{dC_M}{d\alpha}<0$. The selected shape 2-D Bridge deck is stable between the angle of attack 4° up to 6° for both simulation and experiment. However, the experiment results unstable at the angle of attack 6° up to 8° and stable again after that.

The static analysis only part of the whole research on the wind engineering. Furthermore the characteristic static aerodynamic will use in term of dynamic stability of 2-D and 3-D dynamics stability.

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References

[1] M. Suangga and Subagyo, Perencanaan Ketahanan Angin Jembatan Cable-Stayed Suramadu, Seminar dan Pameran HAKI 2008. Pengaruh Gempa dan Angin terhadap Struktur, Jakarta, 19-20 Agustus 2008.

[2] Fadilah,H., Subagyo, Fariduzzaman and Novan, R., Studi Geometri Penampang Lintang Dek Jembatan dengan Simulasi Numerik 2D, SIPEKGAN XVI, November 2012.

[3] Subagyo, Fasilitas Uji Terowongan Angin Kecepatan Rendah Indonesia, Jurnal Energi dan Manufaktur, Vol. 6, No.1, April 2013.

[4] Subagyo and Angga D.S., Pengukuran flutter margin jembatan di UPT-LAGG BPPT, Proseding AMTeQ, pp.93-102, 2015.

[5] Salim, S.M. and Cheah, S.C., Wall y+ Strategy for Dealing with Wall-bounded Turbulent Flows, Proc. Intl. MultiConf. Of Eng. Comp. Sci. Vol. II. Hongkong, 2009.

[6] Fluent Inc., FLUENT User's Guide. Lebanon, Cavendish Court, 2006.

[7] Bruno, L. and Khris, S., The Validity of 2D Numerical Simulations of Vortical Structures Around a Bridge deck. Mathematical and Computer Modelling, Vol. 37, pp.795-828, 2003.

[8] Jewel W. Barlow, William H. Rae, Alan Pope. Low speed wind tunnel testing, John Wiley & Sons, 3nd ed.,1984.
[9] Subagyo, Parametric study of roughness influence toward the boundary layer velocity profile on the simulation of Atmospheric Boundary Layer, Jurnal Teknologi Dirgantara, Vol.12 No.2, pp.128-139, 2014.

[10] Matza G.A., Subagyo and R. Wibawa P., Atmospheric Boundary Layer Model on the Indonesian Low-Speed Wind Tunnel, 6th Annual Basic Science International conference, 2016.

[11] Fariduzzaman, Subagyo, Fadilah Hasim and Matza G.A., Geometry Modification For Minimizing The Aeroelastics Effect, APECWW, 2012.

[12] Simiu, E. and Scanlan, R.H. Wind effects on structures. 3rd. edition. New York: John Wiley and Sons Inc, 1996.