Study of Bridge Parameters on Aerodynamic Performance of Steel Arch Bridge

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Abstract. Aerodynamic stability is a condition required in the planning of long span bridges. Not all countries have detailed planning rules for aerodynamic stability. One of the rules that is often referred to for long span bridge planning is the Design Rules for Aerodynamic Effects on Bridges BD 49/01. This paper will discuss the effect of the value of the average wind speed per hour (Vr), mass per unit length (m) and frequency (f) on The Aerodynamic Susceptibility Parameter (Pb), critical velocity of vortex excitation (Vcr), vibration amplitude for vortex excitation (ymax), critical speed for galloping and stall flutter (Vg), and critical speed for classical flutter (Vf) refer to Design Rules for Aerodynamic Effects on Bridges BD 49/01. The value of the average wind speed per hour (Vr), mass per unit length (m) and frequency (f) will be varied for case study of Teluk Mesjid Bridge a steel arch bridge located in Riau Province, Sumatra Island of Indonesia.

Keywords: long span bridge, steel arch bridge, aerodynamic, flutter, vortex

1. Introduction

The use of long span of bridges requires serious attention to the effects of dynamic winds. Since the collapse of the Tacoma Narrow Bridge, dynamic wind action is one of the main concerns for long-span bridges design. There are several phenomena that occur due to dynamic loads on long-span bridges, including flutter, buffeting, and vortex excitation and galloping.

Flutter is a self-excited vibration that occurs due to wind flow to initiate divergence vibration on the bridge deck. This phenomenon might lead to the damages the bridge structure. Buffeting is vibration caused by turbulence of the wind which can cause fatigue in the structure and discomfort of vehicles passing through the bridge. Vortex excitation is resonance vibration that occurs due to separation of vortex flow through an object of the bridge element. Galloping is one of the phenomena of dynamic instability in a long and slim structure or element.
Not many design codes or standards are available that can determine the performance of the bridge to dynamic wind action or more specifically whether a bridge requires the wind tunnel test or not. One of the standards commonly adopted to evaluate the performance of the bridge to dynamic wind action is the Design Rules for Aerodynamic Effects on Bridges (BD 49/01). The objectives of the research are to investigate the effect of the value of the average wind speed per hour \( (V_r) \), mass per unit length \( (m) \) and frequency \( (f) \) on The Aerodynamic Susceptibility Parameter \( (P_b) \), critical velocity of vortex excitation \( (V_{cr}) \), vibration amplitude for vortex excitation \( (y_{max}) \), critical speed for galloping and stall flutter \( (V_g) \), and critical speed for classical flutter \( (V_f) \) refer to Design Rules for Aerodynamic Effects on Bridges BD 49/01. The parametric study was conducted at Teluk Mesjid Steel Arch Bridge located in Riau Province, Sumatera island of Indonesia

2. Methodology
The methodology of this research is as follows.

a. This research is conducted at Teluk Mesjid Bridge, a steel truss bridge Located in Riau Province, Sumatera island of Indonesia
b. The wind speed record from Badan Meteorologi, Klimatologi dan Geofisika (BMKG) were analyzed to estimate the hourly average wind speed of The Teluk Mesjid Bridge.
c. Based on the cross section of the bridge, the geometric constraints, and dynamic parameters of the bridge, the vortex excitation, galloping, stall flutter, and classical flutter were analyzed and classified based on The Design Rules for Aerodynamic Effects on Bridges BD 49/01

2.1 The Design Rules for Aerodynamic Effects on Bridges BD 49/01
The Design Rules for Aerodynamic Effects on Bridges BD 49/01 [1] is one of the standards that set out the design requirement for bridges with respect to aerodynamic effects. This standard is applicable to all highway bridges and foot/cycle-track bridges. In this standard, there are several requirements that can be used to determine whether a bridge requires a wind tunnel test, such as geometric shapes, as well as parameters related to flutter, vortex induced vibration and buffeting phenomena.

The first step to perform an analysis based on the Design Rules for Aerodynamic Effects on Bridges BD 49/01 is to determine the type of bridge. This type of bridge grouping can be used for bridges made of steel, concrete, aluminum or wood, as well as bridges made of composite, the shape of which can be seen in Figure 1.
The requirements in this standard include

A. The Aerodynamic Susceptibility Parameter, $P_b$

The aerodynamic susceptibility parameter, $P_b$, shall be derived in order to categories the structure using the equation:

$$P_b = \left( \frac{\rho b^2}{m} \right) \left( \frac{16 V^2_{cr}}{b L f_B^2} \right)$$

Based on the $P_b$ value, bridges can be categorized into three categories, as shown in Table 1

|   | $P_b$ Value | Description |
|---|-------------|-------------|
| 1 | $P_b < 0.04$ | Bridges are considered to have no significant effect on any form of aerodynamic force, provided that the geometric requirements are met |
| 2 | $0.04 \leq P_b \leq 1.00$ | Bridges are deemed adequate for a wide range of potential aerodynamic phenomena, provided that the geometric requirements are met, and that the vortex, galloping and flutter requirements are met |
| 3 | $P_b > 1.00$ | Bridges in this category are considered very vulnerable to aerodynamic forces |

B. Geometric checks

For the bridge category with $P_b<0.04$ and $0.04 \leq P_b \leq 1.00$, the geometric shape requirements must be met.

C. Critical Wind Speeds for Vortex Excitation

Wind speed critical to vortex excitation which is also called $V_{cr}$ is defined as the velocity of wind flow or the average velocity of turbulent flow, where the maximum aerodynamic force occurs due to vortex shedding. $V_{cr}$ can be ignored for both torsional and vertical bending if it meets one of the following requirements:

- Bridges that have a base frequency of more than 5 Hz.
- The value of the critical wind speed against the lowest vortex excitation ($V_{cr}$), both bending and torsional, is greater than the reference wind speed ($V_{vs}$), where the value of $V_{vs}$ is taken
as 1.25 times the average wind speed per hour ($V_r$).

- In addition, a truss girder type bridge with a value of $\phi < 0.5$.

If one of the requirements above is met, the bridge can be considered as having no potential for the vortex excitation phenomenon.

D. Amplitudes for Vortex Excitation

The amplitude of the vibration to the vortex excitation is also known as $y_{\text{max}}$. These parameters can be grouped into 2, including:

- Vertical Bending Vibration
- Torsional Vibration

The two vibration amplitudes can be said to meet the requirements, if the dynamic sensitivity parameter (KD) has a value less than 30 mm / s2. The KD formula is as follows:

$$KD = y_{\text{max}} \cdot f^2$$

(2)

Where $y_{\text{max}}$ = amplitude of the vibration, $f$ = natural frequency with respect to bending ($f_B$) and torsional ($f_T$).

D. Critical Wind Speeds for Galloping and Stall Flutter

The wind speed critical to galloping and stall flutter is also known as $V_g$. These parameters can be grouped into 2,

- Vertical Movement
- Torsional Movement

A bridge can be said to be stable against galloping and stall flutter if the $V_g$ value, both vertical and torsional, exceeds the $V_{WO}$ value. Namely the wind speed for checking flutter and galloping.

E. Critical Wind Speed for Classical Flutter

The critical wind speed for classical flutter, $V_f$, shall be calculated from the reduced critical wind speed. The bridge can be said to be stable against classical flutter if the $V_f$ value exceeds the $V_{WO}$ value.

2.2. Case Study- Teluk Masjid Bridge

Teluk Mesjid Bridge is an arch bridge located in Siak Regency, Riau. This deck width of the bridge is 10.45 m with a total length of 90 m + 250 m + 90 m. The height of the deck on the Teluk Mesjid Bridge is 34.65 m from the water level.

![Figure 2: Teluk Mesjid Bridge.](image)

Sectional characteristics of the bridges and its first natural frequency for bending and torsional are presented in Table 2.
Table 2. Sectional characteristics and first natural frequency of the bridges.

| No | Bridge Name | span (m) | width of the deck (m) | mass per unit length (kg/m) | $f_0$ (Hz) | $f_T$ (Hz) |
|----|-------------|----------|-----------------------|-----------------------------|-----------|-----------|
| 1  | Teluk Mesjid| 250      | 10.45                 | 11 113.70                   | 0.794     | 1.163     |

3. Results and Discussion

3.1 Design Wind Speed

The wind speed data used in this analysis were obtained from the Meteorology, Climatology and Geophysics Agency (BMKG), which was obtained under the following conditions:

- Average time: 1 hour
- Elevation from ground level: 10 m
- Ground condition: Open area

The wind speed data for this study obtained from the nearest weather station (Sultan Syarif Kasim II Meteorological Station) to the project sites. The basic hourly mean wind speed ($V_{b}$) calculated using wind speed record with extreme value distribution type I. The hourly average wind speed per hour ($V_r$) = 41.11212 m/s

3.2. The Aerodynamic Susceptibility Parameter, $P_b$

The Aerodynamic susceptibility parameter, $P_b$, for the bridges considered in this study is presented in Table 3.

Table 3. The Aerodynamic Susceptibility Parameter $P_b$

| Bridge     | b (m) | M (kg/m) | $V_r$ (m/s) | L(m) | $f_0$ (s⁻¹) | $P_b$ |
|------------|-------|----------|-------------|------|-------------|-------|
| Teluk Mesjid | 10.45 | 11 113.70 | 41.12       | 250  | 0.794       | 0.20  |

Based on the results of the aerodynamic susceptibility parameter, $P_b$, it can be concluded that. Teluk Mesjid Bridge, are considered to be within the scope of these rules, provided the geometric constraints are satisfied, and shall be considered adequate with regard to each potential type of excitation if they satisfy the relevant criteria of vortex excitation, galloping, stall flutter, and classical flutter.

3.3. Analysis on the Critical Wind Speed for Vortex Excitation

For this purpose, the first step that must be taken is to determine the type of bridge. Based on Figure 1, the Teluk Mesjid Bridge is a type 2 bridge. Based on the formula provided in The Design Rules for Aerodynamic Effects on Bridges BD 49/01 The critical wind speed for Vortex Excitation are $V_{crit} = 7.146$ m/s and $V_{crit} = 10.467$ m/s. The $V_{crit}$ on the Teluk Mesjid Bridge have a value less than $V_{vs}$ (1.25 $V_r = 51.4016$ m/s), and the basic bridge frequency is also less than 5 Hz. Therefore, it can be concluded that the Teluk Mesjid Bridge has the potential for the vortex excitation phenomenon.

3.4 Vibration Amplitude Analysis for Vortex Excitation

Since Teluk Mesjid Bridge is a type 2 bridge, According to The Design Rules for Aerodynamic Effects on Bridges BD 49/01 the torsional vibration amplitude can be negligible. The vertical bending vibration amplitude is $y_{max} = 20.24$ mm. To find out whether the vibration amplitude due to vortex excitation meets the requirements, it is necessary to calculate the dynamic sensitivity parameter (KD). KD = 12.76 mm/s². Since the KD value is less than 30 mm/s², then the bridge user inconvenience does not occur. Therefore, the vibration amplitude requirements for vortex excitation are met. So, Teluk Mesjid Bridge has the potential for the vortex excitation phenomenon, but the deviation size
meets the requirements (safe). Based on the analysis results of the critical wind speeds for vortex excitation and amplitudes for vortex excitation, it can be concluded that the Teluk Mesjid Bridge, is susceptible to vortex excitation vibration, but the amplitude still met the requirements.

3.5. Analysis on the Galloping and Stall Flutter

The Teluk Mesjid Bridge is a type 2 bridge so that the vertical movement is negligible. The critical wind speed to galloping and stall flutter calculated by the following provided is $V_{gt} = 40,1061 \text{ m/s}$. To find out whether the Teluk Mesjid Bridge is stable against galloping and stall flutter, a $V_{WO}$ value is needed. The $V_{WO} = 63.6234 \text{ m/s}$. Because the $V_{gt}$ value is smaller than the $V_{WO}$ value, it can be concluded that the Teluk Mesjid Bridge is unstable against the phenomena of galloping and stall flutter. Based on the analysis results of the critical wind speeds for galloping and stall flutter, it can be concluded Teluk Mesjid Bridge are not stable with respect to the effects of galloping and stall flutter, thus these bridges require further investigation using wind tunnel test.

3.6. Analysis on the Critical Wind Speed of Classical Flutter

The critical wind speed against the classical is $V_f = 74.7688 \text{ m/s}$. Because the $V_f$ value is greater than $V_{WO}$, it can be concluded that the Teluk Mesjid Bridge is stable against the classical flutter phenomenon.

3.7. Analysis on the Effect of Hourly Average Wind Speed ($V_r$)

The hourly average wind speed ($V_r$) will affect the Aerodynamic Susceptibility Parameter ($P_b$) as presented in Figure 3. It can be seen that the smaller the hourly average wind speed ($V_r$), the smaller the Aerodynamic Susceptibility Parameter ($P_b$).

![Figure 3](image)

**Figure 3** The Effect of Average Hourly Wind Speed ($V_r$) on $P_b$

Therefore, it can be concluded that the smaller the hourly average wind speed ($V_r$), the more stable the bridge is to aerodynamic phenomena.

3.8. Analysis on the Effect of Mass Per Unit Length (m)

Mass per unit length (m) will affect The Aerodynamic Susceptibility Parameter ($P_b$), vibration amplitude to vortex excitation ($y_{max}$), critical velocity of galloping and stall flutter in vertical or bending direction ($V_{gB}$), and critical velocity of classical flutter ($V_f$) as presented in Figure 4, Figure 5, and Figure 6 respectively. It can be seen that the smaller the mass value per unit length (m), the greater the value of The Aerodynamic Susceptibility Parameter ($P_b$).
The effect of the mass value per unit length (m) on the dynamic sensitivity parameter (KD) can be seen in Figure 5. It can be seen that the smaller the mass value per unit length (m), the greater the dynamic sensitivity parameter (KD) value. The greater the value of the dynamic sensitivity parameter (KD), the greater the inconvenience of bridge users.

The effect of the mass value per unit length (m) on the critical speed of classical flutter (Vf) can be seen in Figure 6. It can be seen that the smaller the mass value per unit length (m), the smaller the critical velocity value of classical flutter (Vf). The Teluk Mesjid Bridge becomes unstable against the classical flutter phenomenon when its mass per unit length (m) is reduced by 30%. Therefore, it can be concluded that the greater the mass per unit length (m), the more stable the bridge is to aerodynamic phenomena.
Figure 6 Effect of Mass Value per Unit Length (m) on Critical Velocity of Classical Flutter ($V_f$)

3.9 Analysis on the Effect of Natural Frequency ($f$)

Changes in the natural frequency value ($f$) will affect the value of The Aerodynamic Susceptibility Parameter ($P_b$), critical velocity of vortex excitation ($V_{cr}$), dynamic sensitivity parameters (KD), critical speed of galloping and stall flutter ($V_g$), and critical speed of classical flutter ($V_f$). The effect of the natural frequency value ($f$) on the Aerodynamic Susceptibility Parameter ($P_b$), can be seen in Figure 7. It can be seen that the smaller the frequency value ($f$), the greater the vulnerability parameter value to aerodynamic force ($P_b$). The effect of the natural frequency value ($f$) on the critical velocity of vortex excitation ($V_{cr}$) can be seen in Figure 8. It can be seen that the smaller the frequency value ($f$), the smaller the critical velocity value for vortex excitation ($V_{cr}$).

Figure 7 Effect of natural Frequency Value ($f$) on Vulnerability Parameters to Aerodynamic Force ($P_b$)
Figure 8. Effect of Frequency Value (f) on Critical Speed of Vortex Excitation ($V_{cr}$)

Figure 9. Effect of Natural Frequency Value (f) on Dynamic Sensitivity Parameters (KD)

Figure 10. Effect of Frequency Value (f) on Critical Speed of Galloping and Stall Flutter ($V_g$)
The effect of the natural frequency value \( (f) \) on the dynamic sensitivity parameter \( (KD) \) can be seen in Figure 9. It can be seen that the smaller the frequency value \( (f) \), the smaller the dynamic sensitivity parameter \( (KD) \) value. The smaller the value of the dynamic sensitivity parameter \( (KD) \), the less inconvenience of bridge users will be. The effect of the natural frequency value \( (f) \) on the critical speed of galloping and stall flutter \( (V_{g}) \) can be seen in Figure 10. It can be seen that the smaller the frequency value \( (f) \), the smaller the critical speed value for galloping and stall flutter \( (V_{g}) \). Therefore, it can be concluded that the greater the frequency \( (f) \) value, the more stable the bridge is to aerodynamic phenomena.

4. Conclusions
The smaller the average wind speed per hour \( (V_{r}) \), the more stable the bridge is to aerodynamic phenomena. The smaller the mass value per unit length \( (m) \), the greater the value of the dynamic sensitivity parameter \( (KD) \). The greater the value of the dynamic sensitivity parameter \( (KD) \), the greater the possibility of bridge user inconvenience. The smaller the mass value per unit length \( (m) \), the smaller the critical velocity value for classical flutter \( (V_{c}) \). The greater the mass per unit length \( (m) \), the more stable the bridge is to aerodynamic phenomena. The smaller the frequency \( (f) \), the greater the susceptibility parameter value to aerodynamic force \( (P_{b}) \). The smaller the frequency value \( (f) \), the smaller the critical velocity value for vortex excitation \( (V_{cr}) \). The smaller the frequency value \( (f) \), the smaller the dynamic sensitivity parameter value \( (KD) \), and vice versa. The smaller the value of the dynamic sensitivity parameter \( (KD) \), the less inconvenience of bridge users will be. The smaller the frequency value \( (f) \), the smaller the critical speed value for galloping and stall flutter \( (V_{g}) \). The smaller the frequency value \( (f) \), the smaller the critical speed value for the classical flutter \( (V_{f}) \).

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