Aerodynamic stability of suspension bridges

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Aerodynamic Stability of Suspension Bridges

Stabilité aérodynamique des ponts suspendus

Aerodynamische Stabilität von Hängebrücken

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Since the disaster with the Tacoma Narrows Bridge the problem of aerodynamic stability and critical wind velocity has been worrying all suspension bridge designers.

The investigations made in connection with the Tacoma Narrows Bridge [1], [2], [3] and several other bridges [4], [5], [6], [7] prove that an answer to this problems may always be found with the use of model tests. The tests further demonstrate an extremely good correlation between full model tests and the section model tests [1], [5] and in future there seems to be little reason for using a full model in such investigations. However, the tests cost a lot of money and, more important, they take time.

In the investigation of alternatives at an early stage the designer usually will have little or no knowledge of the critical wind, and subsequently of the possibility of building the bridge he is investigating. The trouble with the model investigations, and anxiety of getting into trouble, may result in the choice of other bridge systems, even though the suspension bridge is economically superior.

However, it is possible to predict a critical wind velocity which should be within $\pm 10\%$ of the correct one.

The late Dr. Friedrich Bleich introduced the "Flutter" theory in the investigation of critical wind velocity [2], [8], [9]. The Flutter theory, well known from aerodynamics [10], [11], [12], give the critical wind for a section consisting of a thin plane plate with the wind direction coinciding with the plane of the plate. This flutter velocity (v_F) is easily calculated as demonstrated by Bleich [8]. The calculation may be greatly simplified by representing the results in a diagram as shown in fig. 1, instead of the tables given by Bleich.

However, the bridge will never have a cross-section as a plane plate and the wind will sometimes blow with an angle to the bridge deck plane.

In interest of the Norwegian Administration of Public Roads the Author carried out some systematic section model tests of several Norwegian suspension bridges, fig. 2. The tests demonstrated that the critical velocity v_c is given by a formula

$$v_c = k \cdot v_F,$$

where k is a coefficient mainly depending on the cross-section and the angle of wind attack. The coefficient k may for various sections be taken from diagrams. In fig. 3, 4, 5 some diagrams are given for one of the sections tested. The factors ν and μ, see fig. 1 are $\nu \approx 1{,}1$; $\mu \approx 0{,}018$.

The majority of Norwegian suspension bridges will not differ much from these values [13]. The factors ν and μ will have some influence on the diagrams,

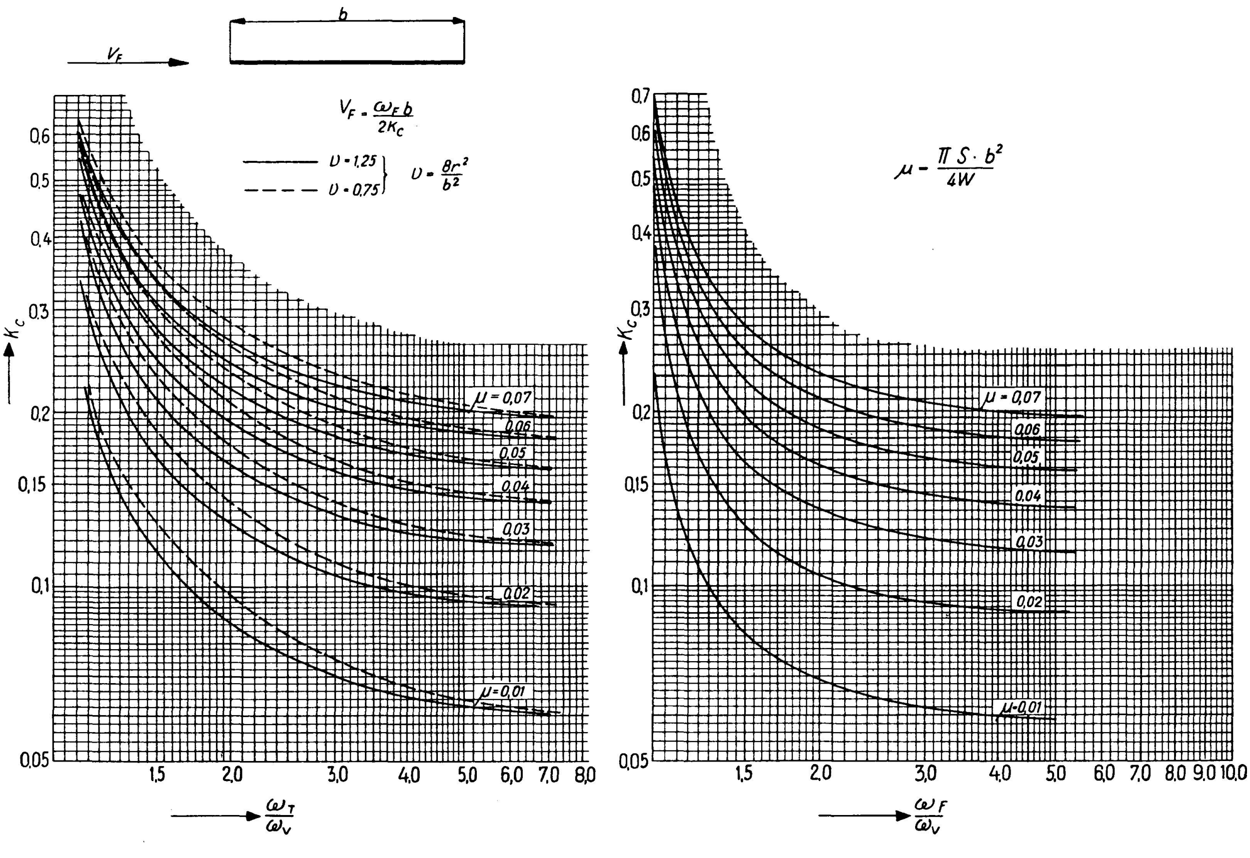

Fig. 1. Flutter Velocity V_F.

S = 0.001283 t/m³ = Dencity of Air.
W = Weight of Bridge — pr. m. and pr. Cable.
r = Mass radius of Gyration.
$\omega_V = \frac{2\pi}{T_V}$ Circular Frequency in Vertical Oscillation.
$\omega_T = \frac{2\pi}{T_T}$ Circular Frequency in Torsional Oscillation.
$\omega_F = \frac{2\pi}{T_F}$ Circular Frequency Flutter Oscillation.
b = Width of Bridge Deck.

especially for greater values of d/b. Complete test results will be found elsewhere [14].

As will be seen from the diagrams the relation between vertical and torsional frequencies $\frac{N_T}{N_V} = \frac{\omega_T}{\omega_V}$ has a marked effect on the coefficient k.

In a section which is a plane plate the oscillations start at a velocity v_F, and the oscillations will increase catastrophic. For other sections, and when the wind attacks at an angle, there will be no such violent rise in the oscillations; increase of the wind velocity will increase the oscillations at the same time. As critical wind velocity, v_1, is therefore in the tests used the highest wind velocity where an initiated oscillation of ± 0.01 rad. ($0° 35'$) will decrease or remain stable.

This defined velocity will coincide with the flutter velocity v_F on sections with a typical flutter effect. For all other sections the defined critical velocity will be on the safe side. However, only a slight increase in velocity will usually raise the oscillations to for instance ± 0.1 rad. ($5° 50'$).

The velocity v_2 is the wind velocity where an initiated oscillation ± 0.1 rad. will remain stable or decrease, and v_3 is the same for an initiated oscillation of ± 0.2 rad.

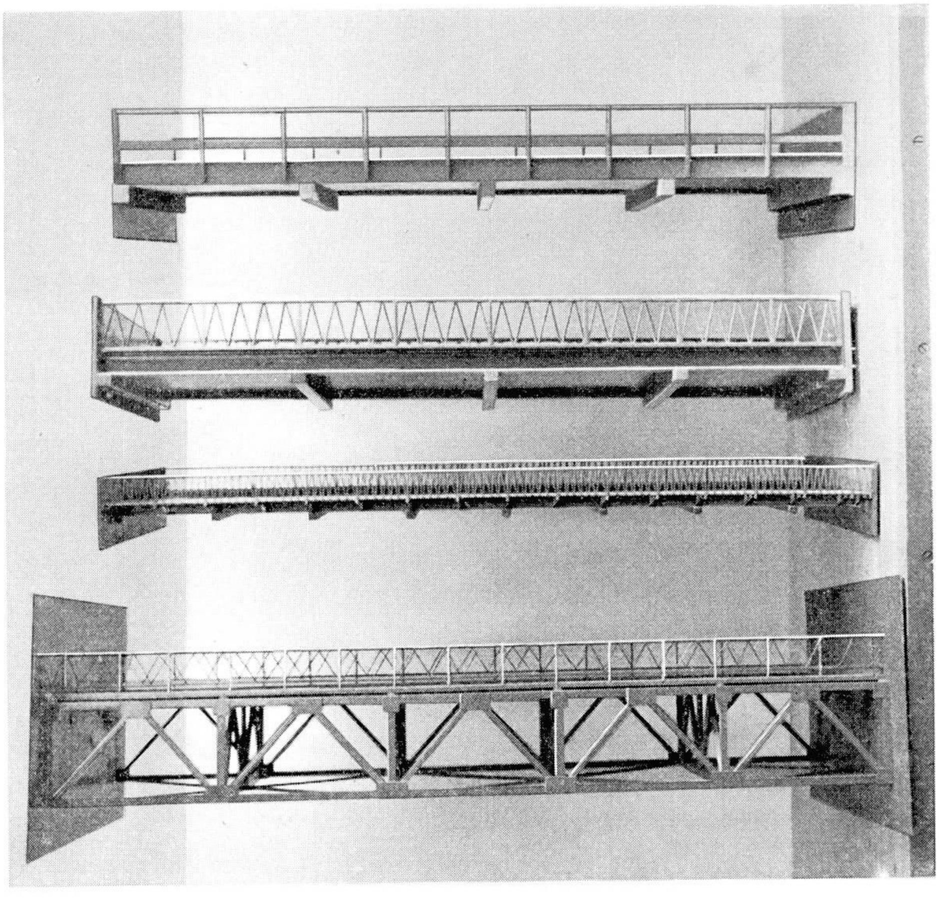

Fig. 2. Some of the Tested Models.

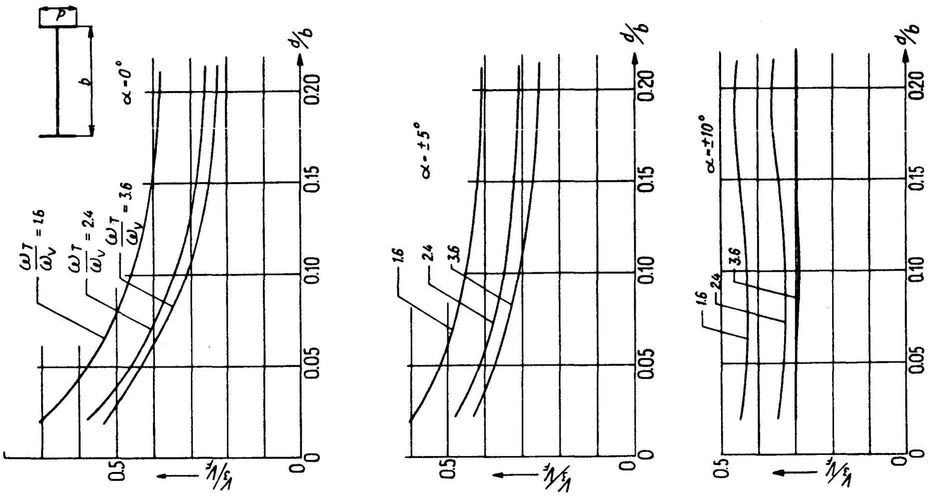

Fig. 3. Velocity V_1 Oscillations $\varnothing \leqq 0.01$ Rad.

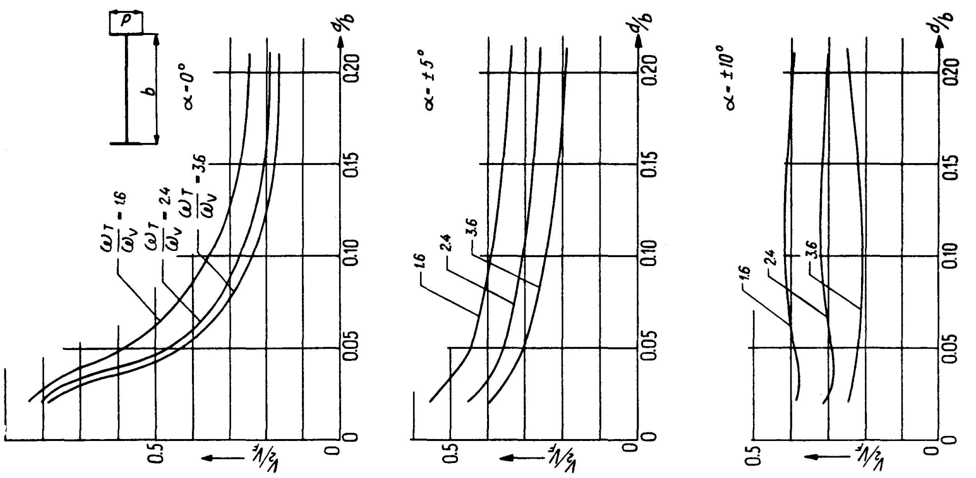

Fig. 4. Velocity V_2 Oscillations $\varnothing \leqq 0.1$ Rad.

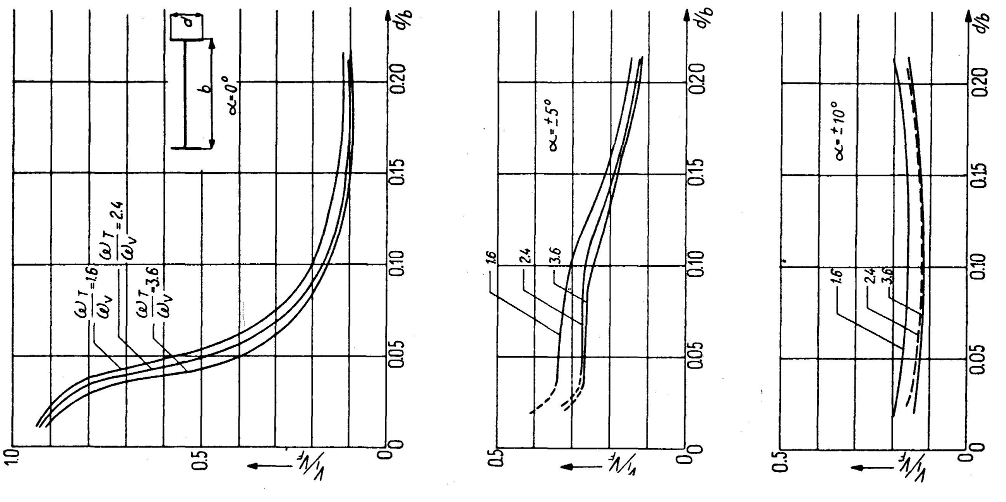

Fig. 5. Velocity V_3 Oscillations $\varnothing \leqq 0.2$ Rad.

A well designed bridge should be able to withstand an oscillation of ± 0.1 rad. for several hours. However, an oscillation ± 0.2 rad. will become catastrophic after a short time.

Comparison between tests made with simplified sections, fig. 6, and several different bridge sections, fig. 2, demonstrated that the deviation from the idealized section may be considerable before having a marked effect on the velocities v_1, v_2 and v_3. Especially the effect of open trusses, handrails, etc. will be small.

The effect of deviation between wind direction and plane of bridge deck is important, however; the full effect of reduction in velocities v_1, v_2, v_3 is practically reached already for a deviation $\alpha = \pm 5°$, and it seems sufficient to give the effect for $\alpha = 0$, $\pm 5°$ and $\pm 10°$. The variation of v with α is demonstrated in detail in fig. 7.

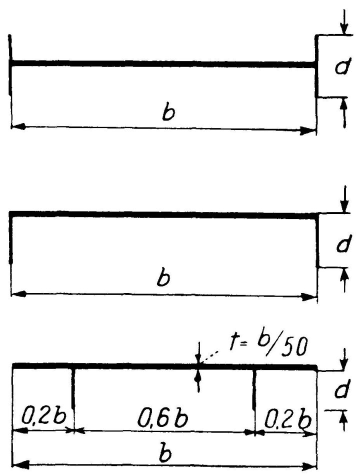

Fig. 6.

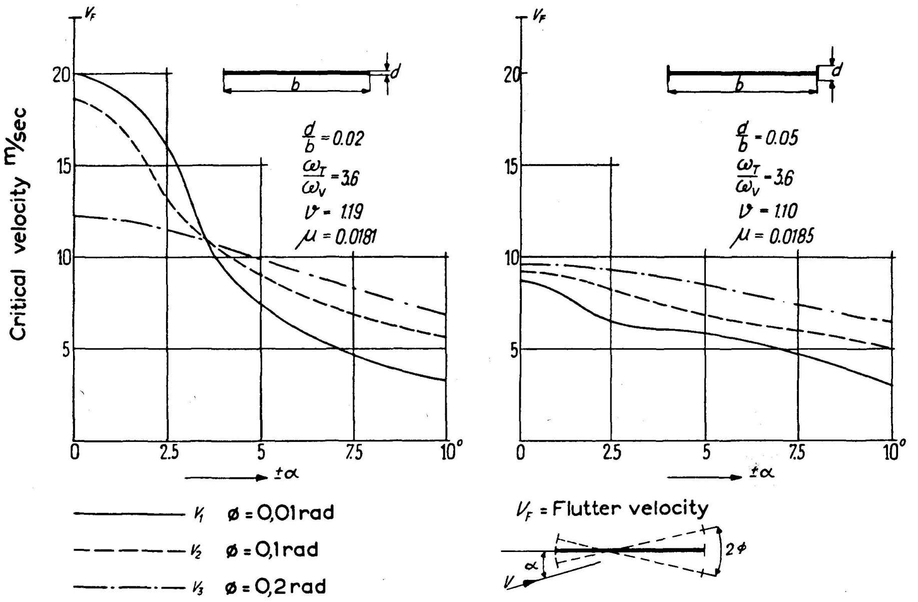

Fig. 7.

For bridges lying close to the water, for instance with height above water not greater than the bridge width, it seems reasonable to calculate as if the deviation α is small. This will usually give a considerable increase in critical velocity.

If we have to calculate with deviations $\alpha = \pm 5°$ or $\pm 10°$, the critical velocity is practically independent of the cross-section. The direction of the natural wind will be constantly varying, and it seems reasonable to avoid sections giving the same low velocity for all angles. For $\vdash\!\dashv$ and $\sqcap$ sections for instance, there is no reason for using sections with $\frac{b}{d} > 0.1$.

The wind in a wind tunnel is far more uniform than in nature. Fig. 8 demonstrates a piezometric measuring of the variation of velocity and direction of the wind, measured in a horizontal plane, during a storm. Some of the gusts go up to 39 m/sec, and the gusts last a few seconds. As the wind has to last several minutes to build up an important oscillation, it seems to be justi-

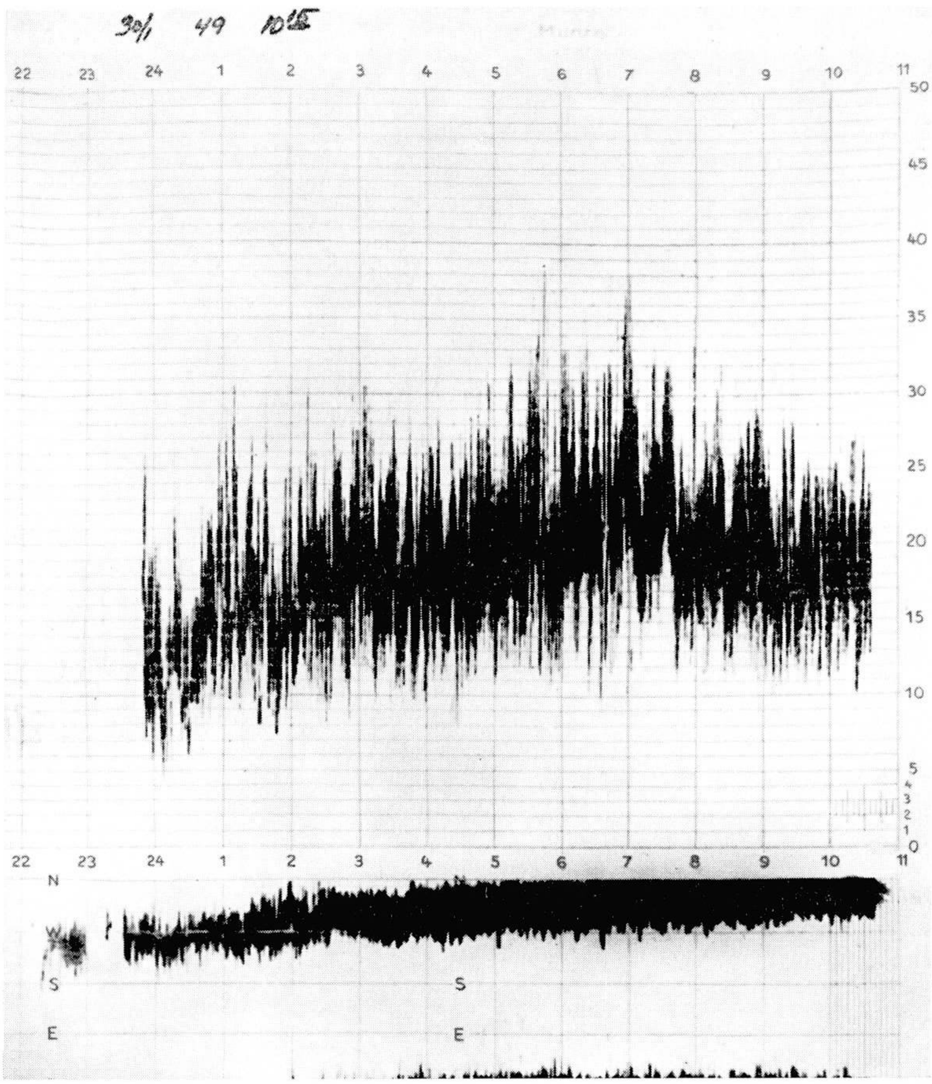

Fig. 8. Measurement of Wind Velocity and Direction.

fied to fix the aerodynamic critical wind velocity somewhat lower than the safe gust velocity. If the bridge safely withstands a wind gust of for instance 65 m/sec, the aerodynamic critical wind should be fixed at say 50 m/s.

One of the reasons for this is that an average wind of 50 m/s, lasting for several minutes and uniform over the entire span will something more improbable than the maximum load on a road bridge or a uniform wind gust on a bridge.

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Summary

With use of diagrams the critical wind velocity may be found within a limit of $\pm 10\%$. Considering the uncertanties connected with the wind this should be more than sufficient for most cases.

Résumé

Pour l'emploi des diagrammes, la vitesse critique du vent peut être déterminée dans les limites de $\pm 10\%$. Compte tenu de l'imprécision dont sont entachées les hypothèses relatives à la charge due au vent, la valeur critique ci-dessus peut être considérée comme plus que suffisante dans la majorité des cas.

Zusammenfassung

Bei Verwendung von Diagrammen kann die kritische Windgeschwindigkeit in einer Grenze von $\pm 10\%$ bestimmt werden. Bedenkt man mit welchen Ungenauigkeiten die Annahme der Windlast behaftet ist, so sollte dieser Wert in den meisten Fällen mehr als genügen.