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Parametric analysis of a flat solar tracker stability curve using aerodynamic derivatives

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SUMMARY:
The stability curve of a two-dimensional flat solar tracker is calculated using the aerodynamic derivatives A_2^* and A_3^* obtained experimentally for different height-chord ratios, H/B. The structural stiffness, K^{mech}, the damping coefficient, ξ^{mech}, and the height of the tracker, H, are modified to study the sensitivity of these parameters on the stability.

Keywords: Solar tracker, Aerodynamic Derivatives, Flutter instability

1. INTRODUCTION

The increase in energy consumption is between 1% and 5% per year depending on the development of the region (Carrión et al., 2008). The increase in the global population and the increased use of lifestyle technologies lead to this sustained increase in energy consumption. In this scenario, the use and development of renewable and carbon-free energies is essential to mitigate the impact of energy consumption.

In this high energy demand background, it is estimated that single-axis flat solar trackers will generate 40% of all solar energy (Fisher et al., 2020) and they are a technological solution of great growth and interest. In addition, it is a technology with little product differentiation due to the simplicity of design. For those reasons, the combination of high demand and low product differentiation has made the flat solar tracker market highly competitive. This competitiveness has resulted in the continuous attempt, by manufacturers, to reduce structural cost and therefore to produce increasingly less rigid structures.

The reduction of structural stiffness has led to the emergence of aeroelastic phenomena such flutter. The aim of this work is to analyse the influence of the structural stiffness, K^{mech}, the structural damping, ξ^{mech}, and the ratio between the height H and the chord B of the solar tracker, H/B, on the critical speed of the system under bidimensional conditions. The critical speed, U_c, is the speed above which the solar tracker shows flutter. Therefore, if the critical speed is plotted as a function of the nominal operating angle of the tracker, α_n, the stability curve is obtained, which delimits the stable and unstable operating regions.

To analyse the stability of the system, the small perturbation formulation presented by (Robert H. Scanlan and John J. Tomko, 1971) using the aerodynamic derivatives is applied. For this purpose, the aerodynamic derivatives of a flat-plate solar tracker under two-dimensional conditions for different H/B ratios and different nominal angles of operation have been calculated at the IDR/UPM facility. An example of the dimensionless aerodynamic derivative A_2^* as a function of reduced speed based on the natural frequency, $U_r = U_\infty/(Bf_n)$, for $\alpha_n = 20^\circ$ and $\alpha_n = -20^\circ$ and $H/B = 0.3$ is shown in figure 1 left.

2. METHODOLOGY

For this study, a solar tracker with the following characteristics has been defined as reference: $B = 4$ m, $H/B = 0.5$, $J^{mech} = 170$ kgm^2, $K^{mech} = 10000$ Nm and $\xi^{mech} = 0.08$ for a length of $L = 1.7$ m. To calculate the critical speed of this tracker as a function of the nominal operating angle, α_n, firstly the static problem, defined by the equation

$$K^{eff}\Delta\alpha_s = \frac{1}{2}\rho U_\infty^2 B^2 C_m(\alpha_{mean}^{eff}) \tag{1}$$

is solved, where K^{eff} is the effective system stiffness per unit length, $\Delta\alpha_s$ is the static deflection of the tracker, C_m is the moment coefficient on the axis and α_{mean}^{eff} is the effective mean angle of attack, $\alpha_{mean}^{eff} = \alpha_n + \Delta\alpha_s$.

Once the static problem is solved and the effective mean angle of the solar tracker is calculated, the dynamic problem defined by

$$J^{mech}\Delta\ddot{\alpha} + C^{mech}\Delta\dot{\alpha} + K^{mech}\Delta\alpha\frac{1}{2}\rho U_\infty^2 B^2\left[kA_2^*(k)\frac{B}{U_\infty}\Delta\dot{\alpha} + k^2A_3^*(k)\Delta\alpha\right] \tag{2}$$

is considered, where A_2^* and A_3^* are the dimensionless aerodynamic derivatives and $k = f/(BU_\infty)$ is the reduced frequency of the motion.

Since A_2^* can be defined as

$$A_2^* = -\frac{2J^{mech}\left(\bar{C}^{eff} - \bar{C}^{mech}\right)}{\rho B^4\omega}, \tag{3}$$

being $\bar{C} = C/J^{mech}$, equation (2) can be solved iteratively to calculate the wind speed, U_∞, that makes $C^{eff} = 0$. This wind speed shall be considered as the critical speed of the system, U_c.

3. RESULTS

To make the stability analysis of the system easier, an example of the derivative A_2^* as a function of the reduced speed, U_r, will be briefly analysed (figure 1 left). As shown in the figure, the derivative A_2^* starts from $A_2^* = 0$ ($C^{eff} = C^{mech}$, see (3)) and becomes negative as U_r increases ($C^{eff} > C^{mech}$). For a particular value of U_r the tendency changes and A_2^* starts to show positive

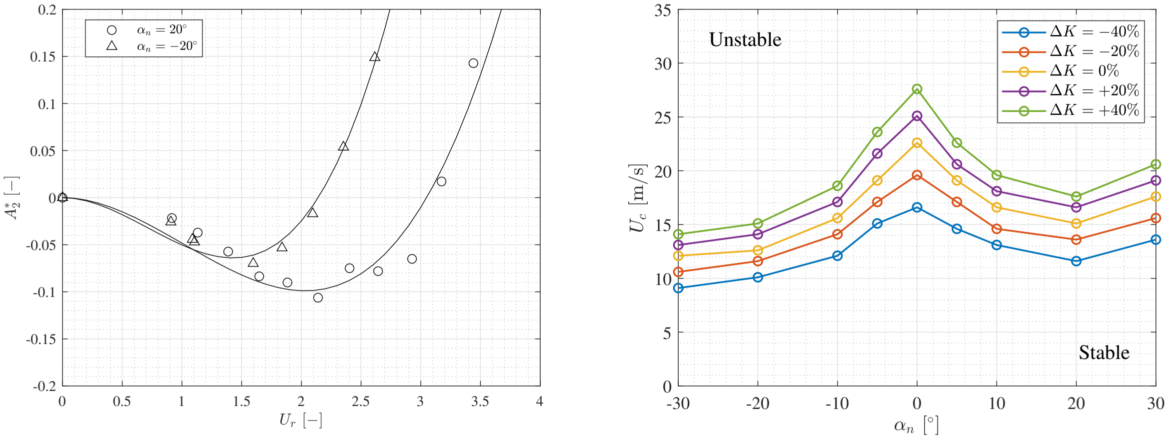

Figure 1. Left: aerodynamic derivative A_2^* as a function of reduced speed, U_r, for $\alpha_n = 20°$ and $\alpha_n = -20°$ with $H/B = 0.3$. Right: critical speed, U_c, as a function of the solar tracker nominal angle, α_n, for different structural stiffnesses, K^{mech}.

values ($C^{eff} < C^{mech}$), this implies that, for these cases of U_r, the aerodynamics tends to decrease the damping and, therefore, the condition of $A_2^* > 0$ is necessary -but not enough-for the instability of the system. The same behaviour of the A_2^* derivative of a flat solar tracker has been reported by Taylor and Browne, 2020.

The stability curves of the solar tracker by modifying the structural stiffness, K^{mech}, are shown in figure 1 right. The $\Delta K = 0\%$ curve is the reference case, whose data is presented in section 2. As shown, increasing the stiffness increases the critical speed. This increase is not homogeneous for the different nominal angles. For small angles, 20% stiffness increase produces an increase of about 5 m/s in the critical speed. On the other hand, for large angles the same stiffness increase produces an increase of about 1 m/s. This behaviour is due to, on the one hand, increasing the stiffness increases the natural frequency of the system, $f_n = 1/(2\pi)\sqrt{K^{mech}/J^{mech}}$, and, therefore, the $A_2^* > 0$ condition is reached for higher wind speeds, U_∞. On the other hand, increasing the stiffness means that the static deflection, $\Delta\alpha_s$, is smaller (see equation (1)) and, therefore, the mean effective angles, α_{mean}^{eff}, will be smaller. As can be seen from the stability curves, lower angles are more stable and, therefore, decreasing the static deflection also contributes to increasing stability.

The stability curves for different damping coefficients are shown in figure 2 left. As it is shown, change the damping coefficient does not mean a change in the critical speeds. This is because as the gradient of the curve A_2^* is very high for the zone with $A_2^* > 0$ (see figure 1 left), modifying the structural damping, C^{mech}, will not change noticeably the value of U_r even if A_2^* changes noticeably. Therefore, modifying the damping coefficient does not significantly modify the critical speed at which the instability begins, although it could affect the amplitude of motion of the tracker once it begins to be unstable.

The stability curves after changing H/B are shown in figure 2 right. As it is shown, the variation of H/B does not change the stability curve so noticeably. The effect that should be highlighted is that as the H/B increases, the curve tends to be more symmetrical between positive and negative

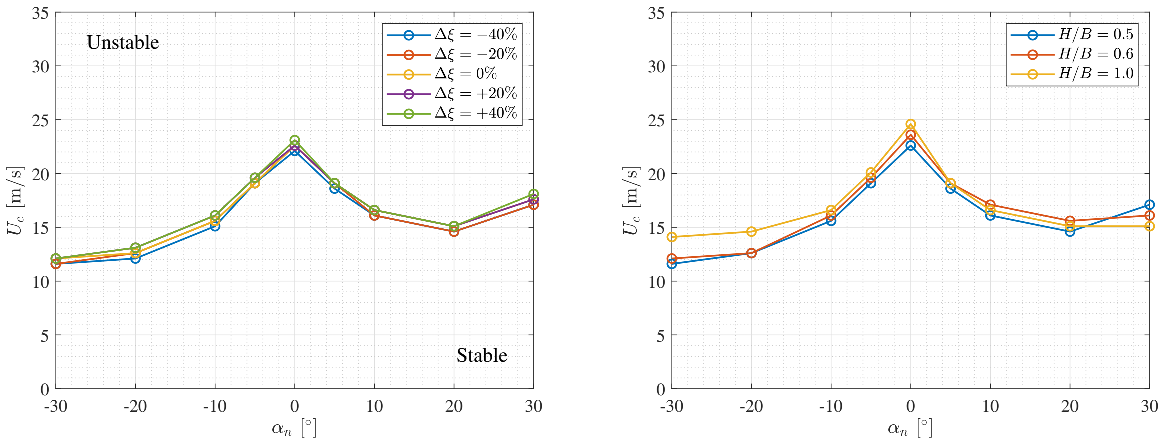

Figure 2. Critical speed, U_c, as a function of the solar tracker nominal angle of attack, α_n. Left: variation of the structural damping coefficient, ξ^{mech}. Right: variation of H/B.

angles, due to the decrease of the ground effect. As it is shown in figure 1 left for H/B=0.3 there is a noticeable difference between $\alpha_n = 20°$ and $\alpha_n = -20°$. What has been observed experimentally is that as the H/B increases the A_2^* derivative of a positive angle and its negative counterpart tend to coincide.

4. CONCLUSIONS

- The parameter that most affects system stability is the structural stiffness of the solar tracker (K^{mech}, figure 1). Increases of 20% in this parameter have resulted in an increase of approximately 5 m/s in the critical speed, U_c, for small nominal angles of operation, α_n, and an increase of approximately 1 m/s for large nominal angles of operation.
- The structural damping of the system, ξ^{mech}, does not modify significantly the stability curve, figure 2 left.
- As H/B ratio increases, the stability curve tends to become more symmetrical, which is to be expected as the ground effect is reduced, figure 2 right.

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