# OPTIMAL SUCTION DESIGN FOR HYBRID LAMINAR FLOW CONTROL

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**Abstract:** We present a theory for computing the optimal steady suction distribution in order to minimize the growth of convectively unstable disturbances, and thus delay laminar-turbulent transition on swept wings. Here, we use the optimal control theory and minimize an objective function based on a sum of the kinetic energy of an arbitrary number of disturbances. The optimization procedure is gradient-based where the gradients are obtained using the adjoint of the parabolized stability equations and the adjoint of the boundary layer equations. Results are presented for an air foil designed for medium range commercial air crafts.

**Keywords:** HLFC, flow control, optimal suction, Tollmien-Schlichting, PSE, adjoint

## 1. INTRODUCTION

The stabilization effect of steady boundary layer suction on disturbance growth has been known for a long time, see Schlichting, 1943, and has been utilized for laminar flow control, for an extensive review see Joslin, 1998. However, in most cases the design of suction distributions rely on the experiences of the engineers which may not always give the optimal solution, i.e. giving the largest delay of laminar-turbulence transition for a given suction power. In the recent decade, the development of optimal control theory applied in ßuid mechanics problems has been rapid and a number of attempts have been made to optimize the steady suction distribution in order to control growth of disturbances Airiau et al., 2003, Balakumar and Hall, 1999, Cathalifaud and



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Luchini, 2000, Pralits et al., 2002 . In all of these investigations the optimization methods are gradient based and they utilize the potential of adjoint methods to obtain the gradients of interest. A common approach is to minimize some measure of the disturbance growth, either the disturbance kinetic energy or the so called $N$-factor. In real applications the steady boundary-layer suction is usually done through a number of discrete pressure chambers, see e.g. Atkin, 2000, Bieler and Preist, 1992, Joslin, 1998. The suction velocity is then a function of the surface porosity, hole geometry and the pressure difference between the pressure distribution on the wing and static pressure in the chambers. In this case, the size and position of the boxes, and the internal static pressure of each box are the design variables, and the suction distribution is given by the specific choice of these parameters.

## 2. PROBLEM FORMULATION

We assume the laminar-turbulence transition is caused by breakdown of convectively unstable disturbances inside the boundary layer. Our aim is to Þnd the distribution of wall-suction such that the growth of these disturbances is minimized. We formulate the problem using the optimal control theory, where a suitable objective function is to be minimized. Here, we choose the objective function to be an integral of the disturbance kinetic energy defined as

$$E = \sum_{k=1}^{M} \frac{1}{2} \int_{X_0}^{X_1} \int_{Z_0}^{Z_1} \int_{0}^{+\infty} |\mathbf{u}|_k^2 h_1 dx^3 dx^2 dx^1,$$

where, $x^1$, $x^2$ and $x^3$ are streamwise, spanwise and normal coordinates, respectively, and $h_1$ the scale factor. Notice that $E$ is given as the sum over $M$ different disturbances. The reason for considering more than one disturbance is to ensure that all types of disturbances present in the boundary layer are controlled, see Pralits et al., 2002. The optimization procedure used here is a gradient-based method. An efÞcient way of calculating the gradient of the objective function, when the number of control parameters is large, is to solve the adjoint of the governing equations. Here, the mean flow is given as the solution of the boundary-layer equations for an infinite long swept wing. The evolution of convective disturbances inside the boundary-layer is modeled by the parabolized stability equations (PSE), see e.g. Bertolotti et al., 1992.

We consider two different control scenarios. In the first, the mass ßux on the wall $\dot{m}_{\mathrm{w}} = W_{\mathrm{w}} \rho_{\mathrm{w}}$ is optimized in a continuous control domain $\Gamma_c = [X_{cs}, X_{ce}]$. Here, $W$ is the normal velocity, $\rho$ the density and subscript $_{\mathrm{w}}$ refers to values at the wall. In the second, we consider the available control domain divided into $K$ pressure chambers such that $\Gamma_c = [X_{cs_j}, X_{ce_j}],\ j = 1 \cdots, K$. Each chamber has a fixed length and position and a variable static pressure. The corresponding suction profile in each domain $[X_{cs_j}, X_{ce_j}]$ is then obtained

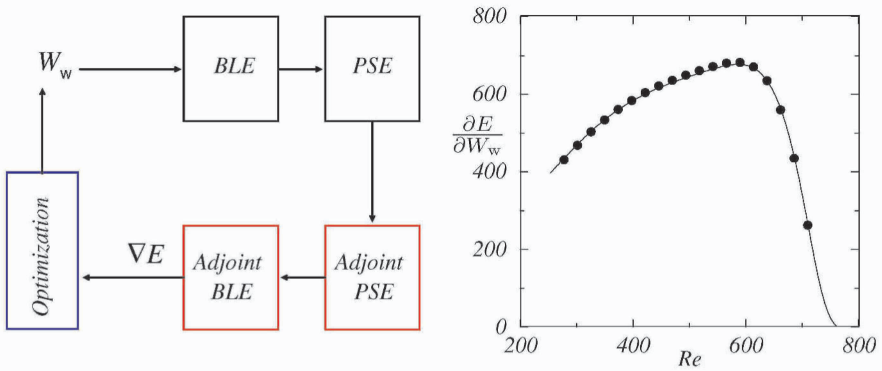


*Figure 1.* Left: Schematic of the optimization procedure for suction distribution. Right: Comparison of calculated derivatives of disturbance energy using Þnite differences and adjoint method. Blasius boundary layer, $F = 10^{-4}$, $\beta = 0$, from Pralits et al., 2002

from the following relation

$$\Delta P_j = P_e - P_{c_j} = \frac{C_1}{\rho_\text{w}} \dot{m}_\text{w}^2 + C_2 \frac{\mu_\text{w}}{\rho_\text{w}} \dot{m}_\text{w},$$

as given in Bieler and Preist, 1992. Here, $P_e$ is the pressure distribution on the wing and $P_{c_j}$ the static pressure in chamber number $j$ and $\mu_\text{w}$ the dynamic viscosity at the wall. The coefficients $C_1$ and $C_2$ depend on porosity of surface and hole geometry, see Pralits and Hanifi, 2003. In this case the static pressure of each box is optimized. The control effort, which is directly related to the power of the suction system, is quantified by the control energy

$$E_C = \int_{X_{cs}}^{X_{ce}} \dot{m}_\text{w}^2 h_1 dx^1.$$

As mentioned before, the solution of the adjoint boundary layer equations, when appropriate initial and boundary conditions are used, gives the desired gradient of the objective function with respect to the mean flow quantities. Instead, its gradient w.r.t. mean mass flow at the wall is given as, see Pralits and Hanifi, 2003,

$$\frac{\partial E}{\partial \dot{m}_\text{w}} = W_\text{w}^*, \qquad \frac{\partial E}{\partial P_{c_j}} = -\int_{\Gamma_j} W_\text{w}^* \frac{\partial \dot{m}_\text{w}}{\partial P_{c_j}} \, h_1 \, dx^1.$$

where $W^*$ is the Lagrangian multiplier of the mean continuity equation. For derivation of the adjoint equations see Pralits and Hanifi, 2003. In Figure 1 (left) a schematic of design procedure for optimal suction distribution is given. In Figure 1 (right) the derivative of the objective function, as a function of the streamwise position, calculated using the adjoint technique and finite differences, are compared. As can be seen there the agreement is excellent.

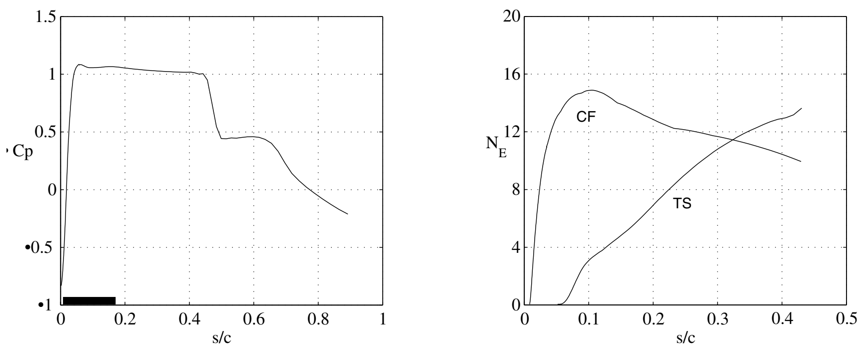


*Figure 2.* Left: Pressure distribution, $C_p$, as a function of the arc-length normal to the leading edge, s/c. The black box shows the domain available for suction systems, $\Gamma_c$. Right: EoE of $N_E$-factor curves for Tollmien-Schlichting (TS) and cross-ßow (CF) waves for zero suction

# 3. RESULTS

The flow studied here is the boundary layer on the upper side of a wing designed for commercial air crafts, see Figure 2. The flow conditions are characterized by a free-stream Mach number $M_\infty = 0.8$, temperature $T_\infty = 230$ K, Reynolds number $Re_\infty = 3.04 \times 10^7$ and the leading edge sweep angle $\phi_{le} = 30.2°$. The pressure distribution of an air foil designed for commercial air crafts can be seen in Figure 2 (left) together with a domain, $\Gamma_C$, available for mounting the suction system. The envelope of envelopes (EoE) of $N$-factor curves, based on the disturbance kinetic energy, for cross flow (CF) and Tollmien-Schlichting (TS) waves can be seen in Figure 2 (right).

In the results shown here, the total disturbance kinetic energy is calculated as the sum of the CF and TS wave with the largest disturbance kinetic energy over a large number of other disturbances. The dimensional frequency and spanwise wave number for these CF and TS waves are ($f_1^* = 5500\, s^{-1}$, $\beta_1^* = 2500\, m^{-1}$) and ($f_2^* = 5750\ s^{-1}$, $\beta_2^* = 225\ m^{-1}$) respectively. In these calculations, the magnitude of the control effort is $E_C = 0.35 Re_\infty^{-1}$. In Figure 3 (left), the optimal static pressures of the chambers (thick lines) are plotted for the cases of 5, 6 and 7 pressure chambers together with the pressure distribution $P_e$ of the wing (thin lines). To show the details, the region s/c=[0.05,0.175] has been magnified. As it is shown there, the pressure drop $\Delta P_j = P_e - P_{c_j}$ is larger close to the leading edge and decreases downstream.

The suction distributions corresponding to the optimal static pressure in Figure 3 (left) are plotted in Figure 3 (right). Note that the uppermost streamwise suction distribution in each case is due to a stagnation line control and is taken to be fixed. For each case in Figure 3 (right), a comparison is done with a

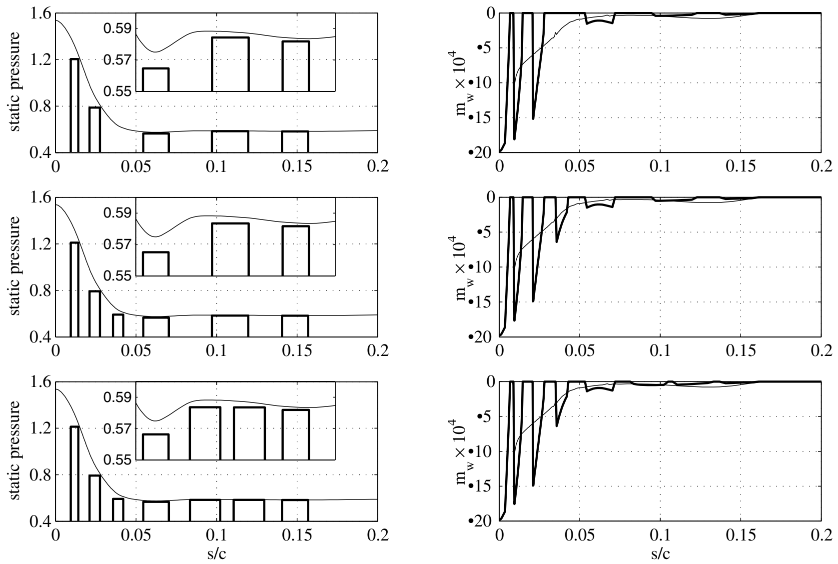


*Figure 3.* Left: Pressure distribution on the wing (thin lines) and optimal static pressure in the chambers (thick lines) for the cases of 5, 6 and 7 pressure chambers minimizing the disturbance kinetic energy for dominating CF and TS wave with $E_C = 0.35Re_\infty^{-1}$. Right: Corresponding suction distributions (thick lines). A comparison is done with a suction distribution (thin lines) obtained by optimizing $\dot{m}_{\mathrm{w}}$ in a continuous control domain

suction distribution obtained by optimizing $\dot{m}_{\mathrm{w}}$ (thin lines) in a continuous domain. As the same control effort is used in these calculations, a direct comparison of the optimal suction distributions for these cases is possible. It is seen that the distribution using pressure chambers approaches the continuous one when the number of chambers is increased. This is most evident downstream of $s/c = 0.05$.

The effect on the disturbance growth using the optimal chamber pressures for the cases of 5, 6 and 7 pressure chambers is shown in Figure 4 (left). Here the EoE of the $N_E$-factor curves for CF and TS waves are plotted for zero and optimal chamber pressures of all cases (solid lines). The arrows mark increasing number of pressure chambers. A decrease in both the growth of CF and TS waves is obtained in all cases using the optimal chamber pressures calculated here compared to zero control. A comparison is done with EoE of the $N_E$-factor curves which are calculated using the suction distribution obtained by optimizing $\dot{m}_{\mathrm{w}}$ in Figure 3 (right) (dashed lines). It is seen that as the number of pressure chambers are increased, the results within the control domain using pressure chambers approach those using a suction distribution in a continuous control domain. The relatively small effect on the mean flow for the cases in

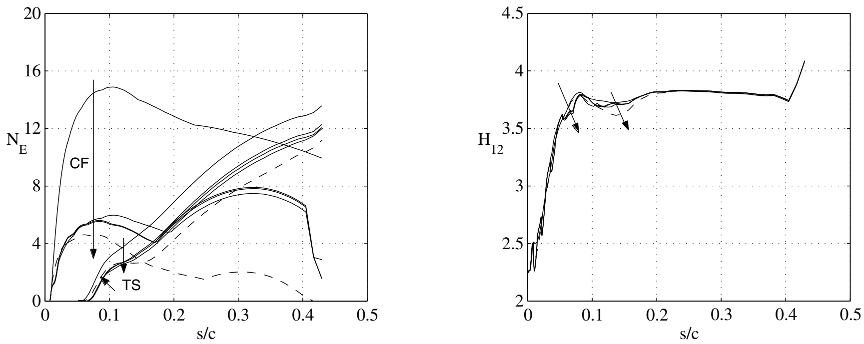


*Figure 4.* Left: EoE of $N_E$-factor curves (solid lines) for CF and TS waves for zero control and the pressure chambers in Þgure 3. Arrows mark increasing number of chambers. Comparison with the EoE of $N_E$-factor curves (dashed lines) given the continuous optimal suction distribution in Figure 3. Right: Corresponding shape factors $H_{12}$

Figure 4 (left) are shown by the shape factor $H_{12}$ in Figure 4 (right).

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