Outline (1/2)

- Team: A. Da Ronch, G. Immordino, University of Southampton, M. Righi, ZHAW and ETH,
- 70 random (LHS) samples in the space:

$$0.74 < M < 0.84, \quad 0 < \alpha < 5^\circ,$$

- CFD indicial responses for each of the 70 points (pitch and plunge "step"),
- Identification of Volterra linear and quadratic kernels,
- NN to reconstruct the kernel coefficients for 3600 uniformly distributed samples in the same (M, α),

Outline (2/2)

- definition of a state space model with linear kernel, dofs: pitch and plunge, m angle of attack values, ($m =$ memory depth),
- assessment of flutter dynamic pressure q_f for 3600 (M, α) combinations, (eigenvalue analysis as function of q),
- estimate of static elastic rotation θ to obtain the wind off angle of attack α_0, to match WT results. We did this with linear and quadratic V kernels,

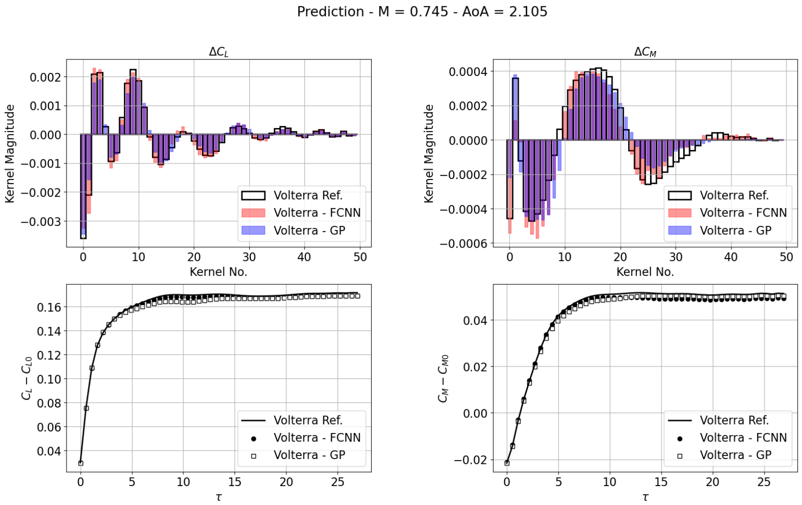
$$\alpha = \alpha_0 + \theta, \longmapsto \alpha_0 = \alpha - \theta,$$

- $\alpha =$ angle of attack, $\alpha_0 =$ AoA wind off, $\theta =$ elastic rotation,

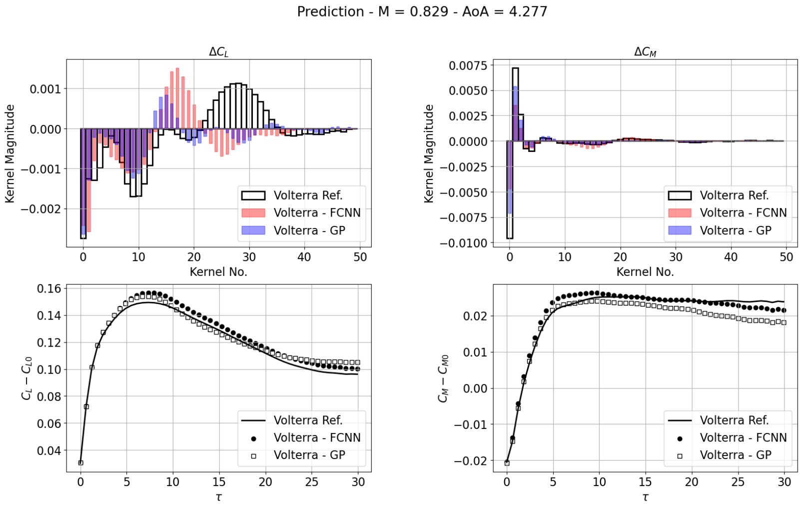
Identification of the Volterra kernels

- Approach by Prof. Dowell (for instance AIAA Journal, Vol. 60, No. 3, March 2022, Levin, Bastos, Dowell, *Convolution and Volterra Series Approach to Reduced-Order Modeling of Unsteady Aerodynamic Loads*),
- The linear kernel is identified separately based on a "small" amplitude signal (0.5° step or smoothed step),
- The higher order kernels are identified as "corrections" to the linear response (1.0° step or smoothed step),
- we (should) identify pitch and plunge separately (ongoing).

Kernels reconstruction $M = 0.745, \alpha = 2.105^\circ$ (1/2)



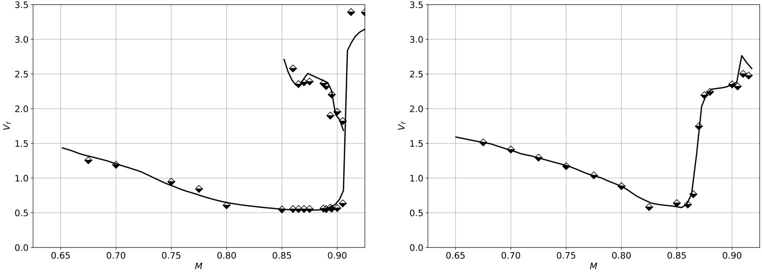
Kernels reconstruction $M = 0.829, \alpha = 0.4277^\circ$ (2/2)



Stability Analysis

- State-space model for pitch, plunge and m past AoA values,
- Eigenvalue analysis in a range of dynamic pressure,
- Alternatively, GAF from indicial responses, and then $p - k$,

Isogai flutter test case, Euler, RANS



(a) Euler

(b) RANS

Figure 1: Flutter index NACA 64a010 (Isogai).

Dynamic stability BSCW, q_f

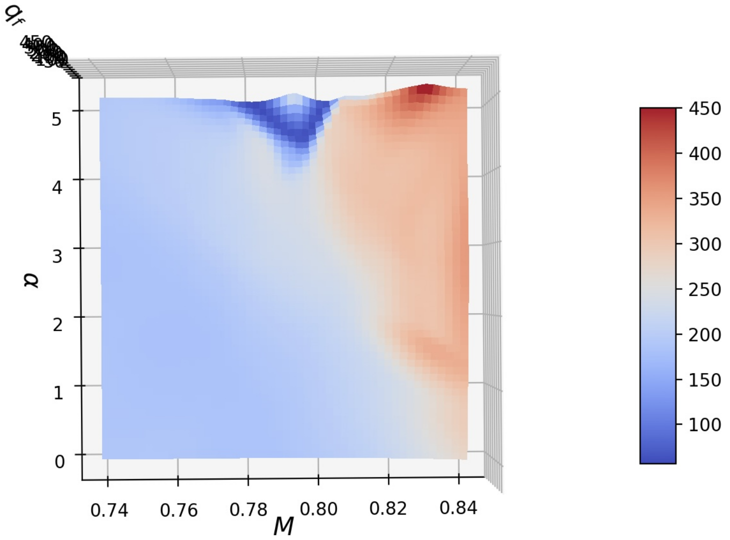
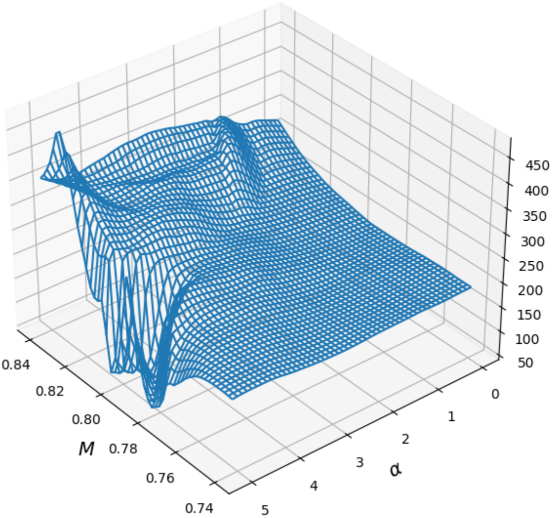


Figure 2: q_f

Dynamic stability BSCW, q_f



Dynamic stability BSCW

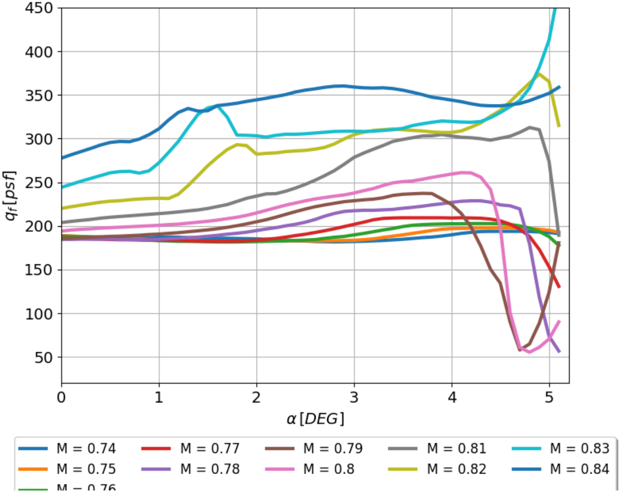


Figure 4: α sweep

Dynamic stability BSCW

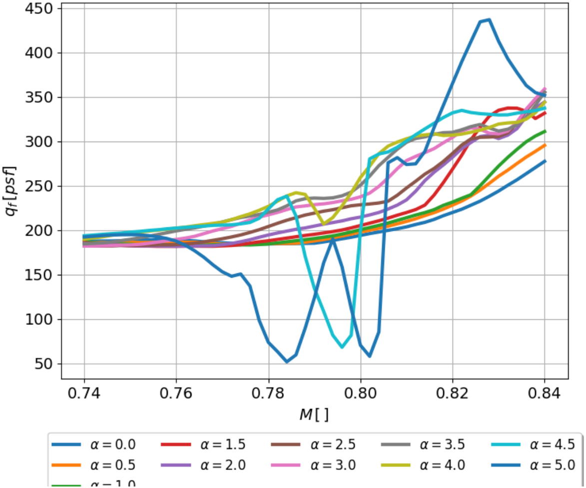
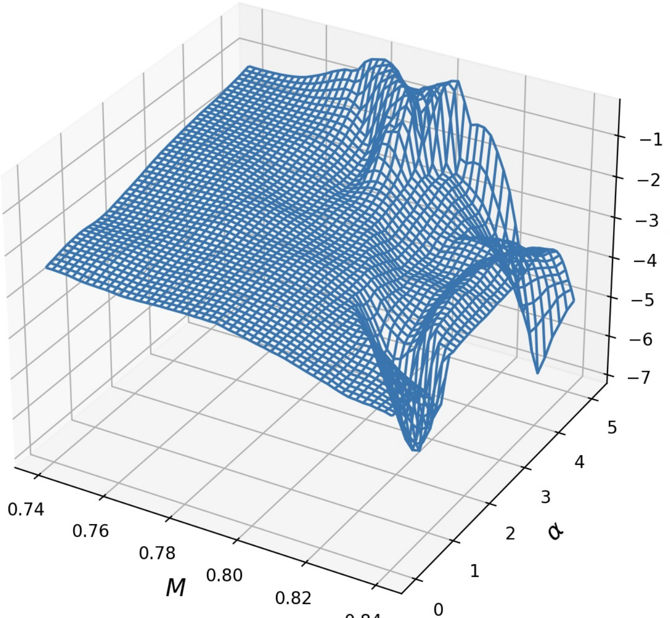
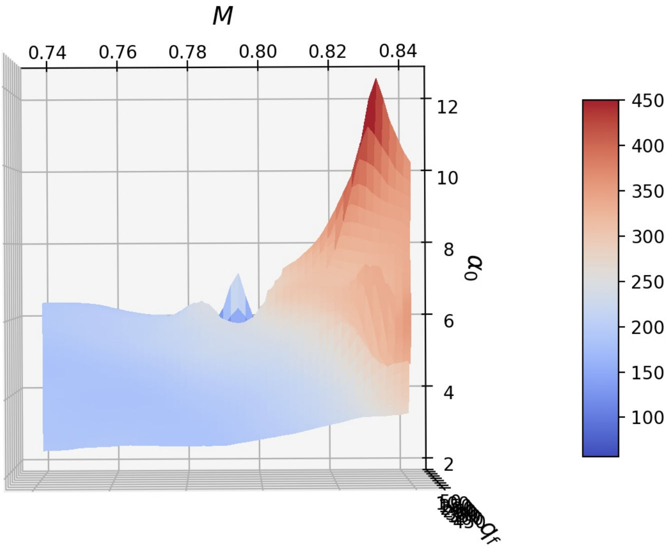


Figure 5: Mach sweep

Static elastic rotation $\theta(M, \alpha)$ for all (M, α) samples, at q_f



Plot of q_f as function of M and α_0 (not α!), i.e. $q_f(M, \alpha) = q_f(M, \alpha_0(M, \alpha))$, whereas $\alpha_0 = \alpha - \theta$



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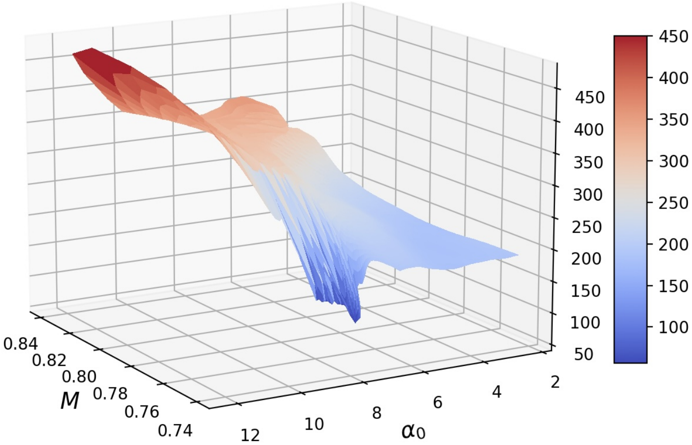
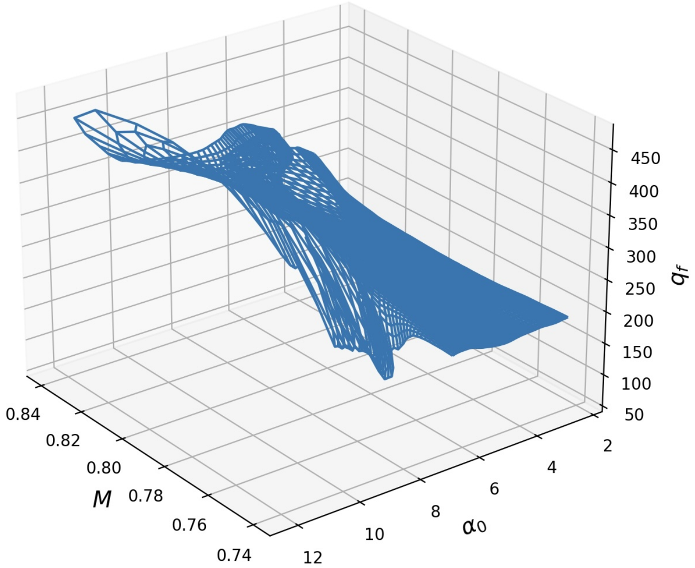
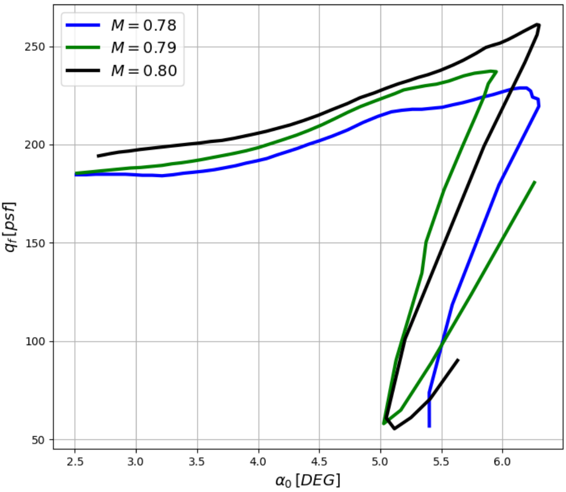


Figure 8: ...

Plot of q_f as function of M and α_0 (not α!), i.e. $q_f(M, \alpha) = q_f(M, \alpha_0(M, \alpha))$, whereas $\alpha_0 = \alpha - \theta$



Plot of q_f as function of M and α_0 (not α!), i.e. $q_f(M, \alpha) = q_f(M, \alpha_0(M, \alpha))$, whereas $\alpha_0 = \alpha - \theta$



Back-Up

State-space model with linear Volterra kernel

$$r^{n+1} = Ar^n, \quad (1)$$

where r includes the dynamic (x) and aerodynamic θ state variables and A is the matrix:

$$A = \begin{bmatrix} A_d & B \\ C & H \end{bmatrix}, \quad (2)$$

State-space system

$$H = \begin{bmatrix} 0 & 0 & 0 & \dots & 0 & 0 \\ h_1 & 0 & 0 & \dots & 0 & 0 \\ 0 & h_2 & 0 & \dots & 0 & 0 \\ \dots & & & & & \\ 0. & 0 & 0 & \dots & h_m & 0 \end{bmatrix}, \tag{3}$$

α^{n+1} is the angle of attack at time $n+1$, B is the matrix:

$$B = qS \left\{ \begin{array}{llll} 0 & 0 & \dots & 0 \\ 0 & 0 & \dots & 0 \\ h_1^{C_l} & h_2^{C_l} & \dots & h_m^{C_l} \\ h_1^{C_m} & h_2^{C_m} & \dots & h_m^{C_m} \end{array} \right\}. \tag{4}$$

and C links the angle of attack to the state variables.