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Signal shapers for BWB aircraft control

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Abstract: This article shows results related to application of impulse signal shapers (ZV, ZVD, EI), applied on reference signal as a feed-forward vibration compensator for pilot commands incorporated with feedback control system (FCS) design for blended-wing-body aircraft (ACFA 2020). The results are nicely indicating ability of connection feed-forward approach for reducing vibration cooperation with active damping. Other goals are study signal shapers design for hard nonlinearities in elevator and ailerons like saturation and rate limiters, induce by finite rates and deflection of servomechanism of control surface. Standard design can't be directly used for higher deflection of elevator and ailerons, because nonlinearities deform shaped command. Two efficient modifications used as alternatives to standard shapers configuration, suggested in the article, permit application of the feed-forward compensation in respect of this setup.

This is preliminary papers for EUCASS conference in Petrohrad 2011

1. INTRODUCTION

Impulse shapers (PosiCast, ZV, ZVD, EI, ...) have been in the centre of attention for last two decades, [1, 2, 3], as an efficient feed-forward approach for vibration control of flexible systems, like cranes, manipulators or flexible mechanical structures [4, 5, 6]. Realisation is based on convolution of a sequence of impulses, an input shaper sets, with desired references. The shaped command cancels vibration which is responsible for excitation of the flexible modes of the aircraft. If the impulses, which is defined the shaper behaviour are chosen correctly, then the system will respond for desired reference without undesirable vibration.
Input shaper as a feed-forward controller can be regarded as a smart filter of the reference signal, an add-on to a functional reference-tracking feedback control system. If the controlled system is flexible, such our aircraft typically features are bending of the hull and wing behavior during pitching maneuver due to excitation of underlying flexible modes by set point changes (step commands), is shaper appropriate alternatives to classic low-pass filters. Therefore, posicast control can be regarded as a complementary measure in a two-degree-offreedom control scheme, when the feedback loop is closed first to guarantee robust stability, disturbance rejection and positioning, and then the input command pre-filter shapes the reference signal such that the transient response is less oscillatory.

2. SIGNAL SHAPERS FOR FLEXIBLE AIRCRAFT

Apparently, signal shapers are clear candidates for inclusion into an efficient FCS for flexible aircraft on figure 1, like the ACFA 2020 blended-wing-body design (www.acfa2020.eu).

Figure 1 The ACFA 2020 blended-wing-body aircraft

For some reason though, signal shapers are not commonly known in the flight controls area and some more traditional solutions, like „structural filters" are routinely used – basically low-pass Chebyshev or other-type filters included in the FCS so as not to excite flexible modes. In comparison, properly tuned signal shapers, targeted at the most prominent flexible modes of the aircraft, lead to superior responsiveness and more efficient vibrations suppression.

The role and placement of a properly designed PosiCast shaper in a traditional feedback SAS (stability augmentation system) or CAS (control augmentation system) is depicted in the following scheme on figure 2(inputs: El-elevator, Ai-aileron, R-rudder). SAS/CAS is not supposed to act as flexible modes damper in the following figure. For a SAS/CAS augmented by (or integrated with) feedback active damping system, the scheme changes as figure 3 (for a particular case of roll autopilot).

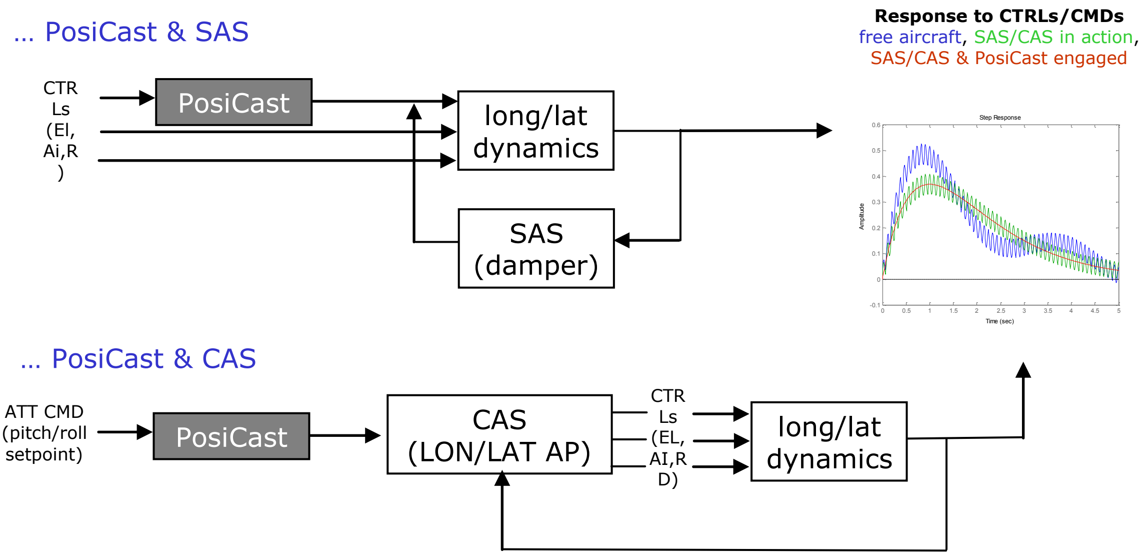

Figure 2 ***Placement and function of PosiCast input command shaper in a feedback SAS/CAS systems***

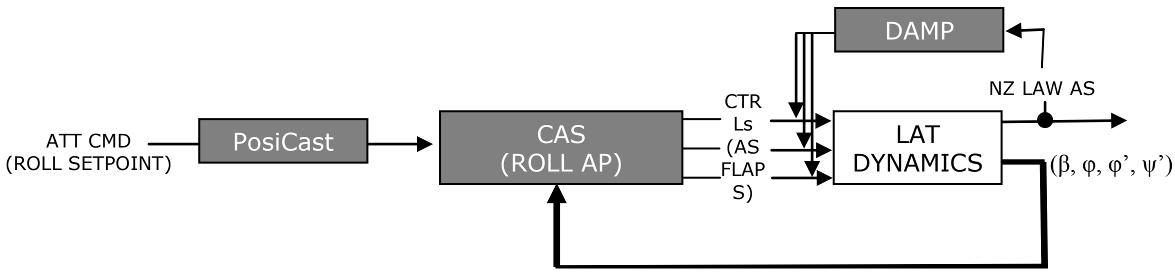

Figure 3 Posicast ***and active-damping-augmented lateral CAS***

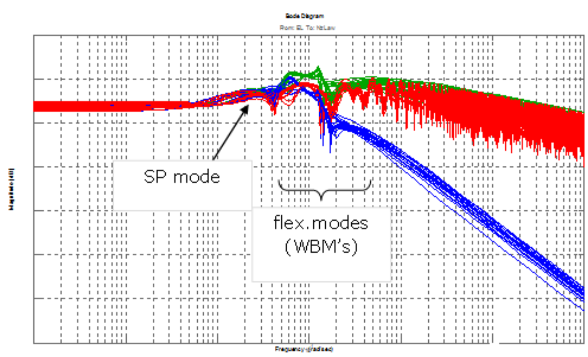

Figure 4 PosiCast and longitudinal NACRE model. Stick to NZ law wings (bode)

3. RESULTS FOR ACFA 2020 BWB AIRCRAFT

First, for the purpose of this extended abstract, a very simple SAS (SISO, stabilizing unstable longitudinal dynamics) is considered and classical PosiCast signal shaper is included in the stick-input channel. The aircraft dynamics is left as unchanged as possible obviously.
Transfer function from stick input to the wings modal sensor (accelerometer-based, Nz Law) is in the figure 4, 5, showing significant damping of wings first two flexible symmetric modes (red), compared to a free aircraft (green) and also to the Chebyshev-type structural low-pass filter (blue). Note that a two-modes (four sub-steps) version of PosiCast was designed to cover both modes simultaneously for all 18 mass cases (6 for fuel, 3 for passengers).

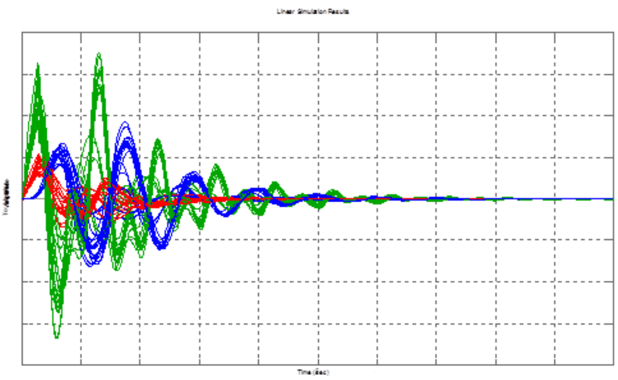

Figure 5 PosiCast and longitudinal control. Stick to modal sensor (step).

The PosiCast shaper certainly affects responsiveness of the aircraft (see the close coupling of flexible and SP modes). In any case nevertheless, it does not affect it more negatively than the structural filter. See the following figure:

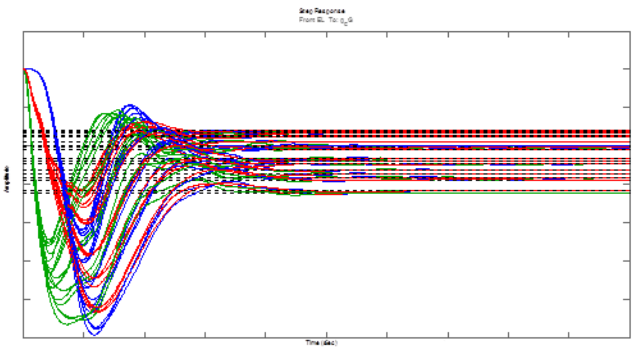

Figure 6 PosiCast and longitudinal NACRE model. Stick to q (step).

In this case, PosiCast is acting directly on the control surface signals where the rate limiters need to be taken into account. All effects described in section 4 are evidenced (posicast out of the game for step stick command and elevator deflection above 5 degrees) and the measures proposed in the next sections (like ramp split-up for higher amplitudes) lead to exactly the same results. Refer to section 4 for detailed description.

In the full paper, further results shall be reported for both longitudinal and lateral ACFA 2020 BWB controls, also in combination with active damping feedback system, figure 7.

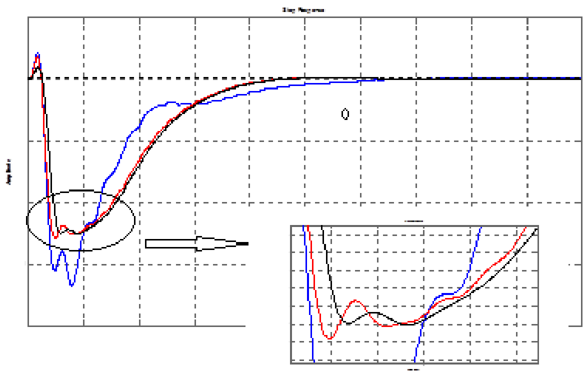

Figure 7 BWB LAT AP (blue,) augmented with active FB damper (red), and with PosiCast on top of that (black). ROLL SP to NZ LAW WINGS antisymmetric (step). Selected passangers-fuel combination (2-5)

Compare the modal sensor reading (LAT CAS, step for roll-angle setpoint), for FCS only (red), FCS+feedback active damper (blue), and with PosiCAST shaper on top of that all. Contribution of the signal shaper in this setup, for reduction of vibrations caused by the automatically engaged maneuver, is obvious. In addition, responses of the aircraft in all cases are almost identical:

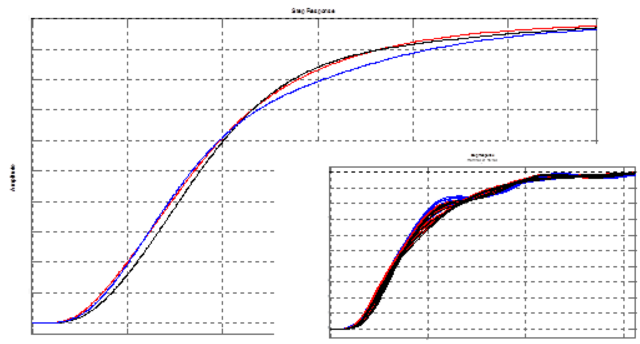

Figure 8 BWB LAT AP (blue,) augmented with active FB damper (red), and with PosiCast on top of that (black). ROLL SP to ROLL ANGLE (step). Selected passangers-fuel combination (2-5, all cases (sub-figure))

4. SIGNAL SHAPERS AND RATE LIMITERS

As shown, delay-based input shaper, like zero vibration and extra insensitive (ZV, EI), can be effectively used as a feed-forward reference filter applied to pilot command in order to reduce wing bending and vertical bending of hull during a maneuver. This strategy is nevertheless strongly limited by the rate limiter nonlinearity (standing for finite servos rates), having substantial, amplitude-dependent filtering effect on the input signal. This observation can be interpreted both in the frequency and time domain terms. Speaking in frequency-

domain words, rate limiter acts as a low-pass filter, with cut-off frequency strongly dependent on the amplitude of the input signal on figure 9.
The higher the amplitude is, the stronger filtering effect arises. By inspection of the dependency on figure 9, for elevator commands greater than five degrees (cut-off approx. 15 rad/s for five degrees amplitude), the influence of the delay-based filters on the command signal is strongly weakened by the rate limiter at the higher frequency of the HBM Considering these facts, filters cannot in principle be successful for all cases

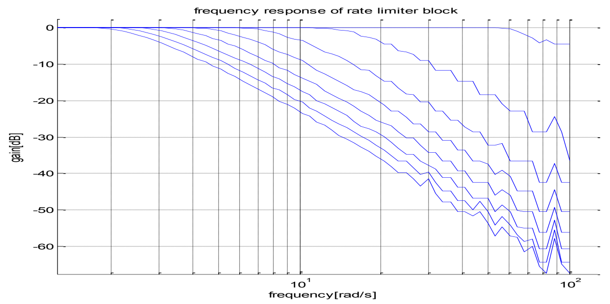

Figure 9 Frequency responses of a 30deg/s rate limiter for varying signal amplitude.

By inspection of the dependency on figure 9, for elevator commands greater than five degrees (cut-off approx. 15 rad/s for five degrees amplitude), the influence of the delay-based filters on the command signal is strongly weakened by the rate limiter, figure 11, at the higher frequency of the HBM Considering these facts, filters cannot in principle be successful for all cases.

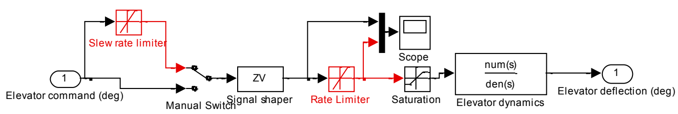

Figure 10 Configuration

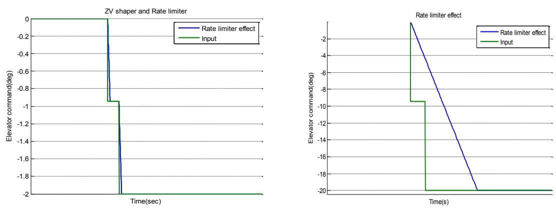

Figure 11 Effect of rate limiter

For this reason, two approaches are suggested. In both cases, the shaped signal is modified in such a way that it becomes tractable through the subsequent rate-limiter block without distortion (unlike the pure signal shaper output itself.
The first approach is based on splitting the ramp signal, coming out from a rate-limiter block as a response to step, artificially, for a time-delay slightly smaller than the ZV shaper-suggested value. This leads to a fair reduction of the HBM peak, figure 12. In this particular case, the shaped reference in the figure 12 for the 20 deg. elevator command, which has transfer function (1),

$$G_{mod} = \frac{1}{spoint}\left(\frac{rate}{s}e^{\frac{-spoint.rate}{2}s}\right) - \left(\frac{rate}{s}e^{-\left(\frac{spoint}{rate}+delay\right)s}\right) + \left(\frac{rate}{s}e^{-\left(\frac{spoint.rate}{2}+delay\right)s}\right) \qquad (1)$$

where spoint is set point, rate is setting of rate limiter and delay is value from posicast approach.

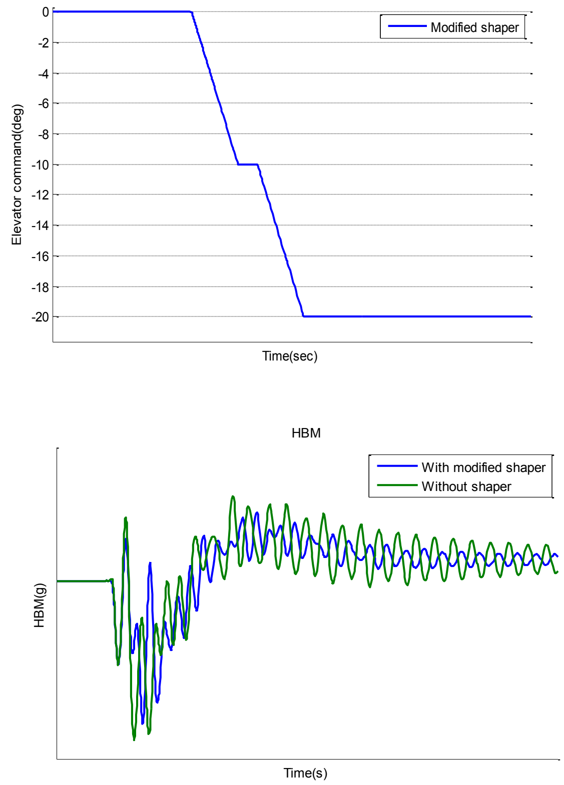

Figure 12 Modified reference shaper and effect on hull bending mode

This command is fully accepted by rate limiters without any distortion. The filter G_{mod} is, unfortunately, parameterized by the amplitude of the step, so it is not a constant, or time-invariant system.

Alternatively, the following procedure can be applied. The main idea is to attach an additional rate limiter, with the same setting as the one representing servos, in front delay-based shaper, figure 10. The modified filtered command is obviously accepted by (passed-through) the finite-rate servos without any distortion, the red line on figure 13, and it does not contain frequencies corresponding to flexible modes of aircraft (as the signal shaper is in the command line). The results of the hull bending sensors on figure 14 show power of this method, where the green line isn't treat by new approach and blue(ZV) and red(EI) line is for different used shapers with naturally adaptive rate limiter before.

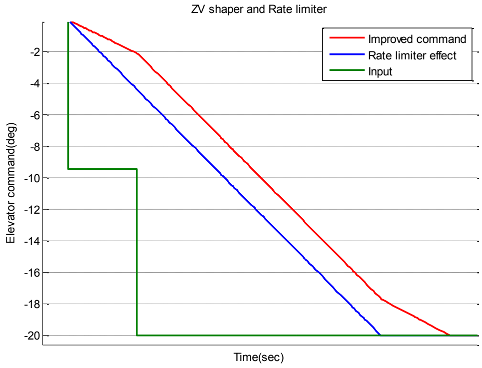

Figure 13 Effect of Rate limiter on shaped reference

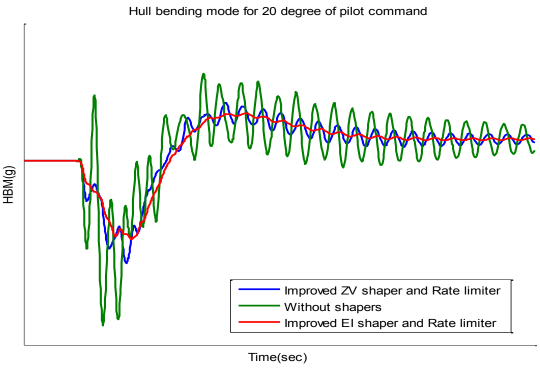

Figure 14 Bending of hull for 20 degree of reference command

CONCLUSIONS

Results will be further developed and applied for the case study of large flexible blended-wing-body aircraft, similarly to section 3 (for the classical signal shapers designs). Data come from the ongoing European project ACFA 2020. ACFA 2020 (Active Control for Flexible Aircraft, www.acfa2020.eu) is a collaborative research project funded by the European Commission under the seventh research framework programme (FP7). The project deals with innovative active control concepts for ultra-efficient 2020 aircraft configurations like the blended wing body (BWB) aircraft.

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