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DESIGN OF WIND SHEAR FILTERS

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16. Abstract

A few design criteria for such filters are given which were found by optimization runs and were then refined using theoretical considerations.

A description is given of the filter types and the control technical boundary conditions. As a result of the study it is found that it is necessary to separate gusts from wind shear components when designing the flight controller.

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DESIGN OF WIND SHEAR FILTERS /**261

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Summary

The requirements for improved path and trajectory control of aircraft during landing approaches can be satisfied using a coupled control system, with respect to conventional controls. When there are wind shear conditions, the desired quiet operation with shear can only be achieved introducing a filter into the control loop, which suppresses the higher frequency gust signals.

A few design criteria for such filters are given which were found by optimization runs and were then refined using theoretical considerations.

/262

1. Introduction

A number of aircraft accidents in the past have been attributed to shear wind defect. Therefore, in this connection, we have considered the problem of improving the path and trajectory control of previous control systems, which can be implemented by either switching in the perturbation variables [1] or by controlling power [2]. Both methods are only of practical value if suitable filters can be found for separating the higher frequency gust wind components from the low frequency shear components. Such filters have to be designed so that, because they are inoperative during thrusting periods, they can be used in all flight phases and do not have to be switched in under conditions of shear winds.

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**Numbers in margin indicate pagination of foreign text

The increase in amplification factors in a control system only improves the trajectory and path control at the expense of thrust quiet operation. Therefore, we must consider the problem of filter design not so much as a parameter question, but more as a structural question for the overall system. In this connection, we have to consider a number of other requirements:

- In order to avoid a misinterpretation of the control system by the pilot, only quantities which make physical sense can be connected to the actuators.

- The required calculation effort must be limited by selecting the most simple structures.

- The control behavior of the overall system must not be influenced by a wind shear filter.

Whether or not these requirements can most easily be satisfied using a perturbation variable switching or a filter in the control loop will be discussed in the following section.

2. Comparison of thrust control law and $\dot{H}_{EL}$- control

The main advantage of a "classical" perturbation variable switching must be seen in the fact that when there are system-independent perturbations, one does not have to continue to wait for a control deviation at the loop output, but instead, one can immediately perform a correction. Figure 1 shows a comparison of the principles. /263
In order to limit the effects of parameter changes, one must use a control loop just like before, but with smaller switching factors. In [1], this led to the derivation of the following thrust control law:

$$\frac{\Delta F}{G} = \frac{\Delta w_{wg}}{V_o} + \frac{\Delta u_{wg}}{V_o} \gamma_o + \frac{\dot{u}_{wg}}{g} \quad . \tag{1}$$

The vertical and horizontal wind components Δw_{wg} and Δu_{wg} have to be then switched into the thrust, just like the horizontal wind gradient $\dot{u}_{wg}$. The filtering of $\dot{u}_{wg}$ is very problematical.

This thrust control law was used by Hohfeld [3] as a basis without consideration of the aircraft dynamics during his filter investigations.

The second possibility is the power control principle for controlling wind shear suggested in [2]. The power change of the aircraft normalized for weight is given by

$$\dot{H}_E = \frac{V_k \dot{V}_k}{g} + \dot{H} \qquad (2)$$

A comparison with the thrust control law is obtained by determining the additional power $\Delta\dot{H}_E$ required in the event of wind disturbances.

After substitution of the corresponding angular relationships and velocity relationships in [2], one obtains an expression which corresponds to the thrust control law, i.e., in other words, we have the relationship

$$\frac{-\Delta\dot{H}_E}{V_0} = \frac{\Delta F}{G} \; . \qquad (3)$$

This relationship is easy to implement, because in both cases, energy deficits caused by wind disturbances can be equalized only by the thrust, the only control variable.

/264

Since, in addition, $\dot{H}_{EL}$-control has the same high dynamic qualities as perturbation variable switching, it is possible to implement this easily using Figure 1 for horizontal wind disturbances. The perturbation variable directly affects the loop output and, therefore, has an immediate control deviation as a consequence.

As also shown in Figure 1, the perturbation variables represent a function of the aircraft state variables. Since in this case we have now violated the condition of system independence from the perturbation variables, we have now lost an important disadvantage of perturbation variable switching: The filter can no longer be designed independent of the aircraft or controller dynamics.

Because of the simpler structure and the clearly reduced measurement-technical complexity, we therefore restricted our investigations to filters for the control loop.

3. Filter types

We can already make a preliminary selection of possible filter types using the condition that the operation must be quiet during thrusting. The previously only possible practical method for evaluating quiet operation during thrusting was the calculation of the thrust change rate $\Delta\dot{F}$, which, howver, does not include the frequency of thrust changes. Figure 2 shows this condition: Both variations have the same quiet operation during thrusting. As an additional criterion for noise loads, we can use the area underneath the curves, that is, the energy supply for the aircraft.

In order to avoid undesirable high frequency thrust changes, it is first natural, for example, to use digital low pass filters of higher order. Figure 3 shows the amplitude variations of various filters without rise errors. The recognizable advantage of the filter higher order, however, is soon lost in practice because the effective filter order is increased by a factor of three because of the low pass behavior of the engine and the decrease in the gust power at high frequencies. In the case of the PD_2T_3-filter, this factor is 6.

One important disadvantage of the higher order filters can be recognized using the ramp responses given in Figure 4. The entrainment error decays more slowly and the thrust noisiness clearly increases because of the increased rise gradient. By selecting other limiting frequencies, one cannot bring about any noticeable change.

/265

The nonlinear statistical filters investigated by Hohlfeld [3] have basically the same behavior as the filters, and do not bring about any noticeable improvements. Therefore, we restricted our investigations to filters without rise errors.

4. Control technical boundary conditions

The mentioned filters are especially suited for investigations in control loops because of their linear structure, which we will now discuss.

The basic system of the aircraft is shown in Figure 5. It has r = 2 input variables, n = 5 state variables and m = 4 output variables. According to theory, it can be shown that for the discussed system, m + r-1, i.e., 5, and therefore, all of the eigen values can be specified with the given input and output variables. If the following conditions are met:

- the system matrix is cyclical, that is, when its minimum polynomial corresponds to the characteristic polynomial, and
- the overall system of each vector of the input matrix and the output matrix respectively can be completely controlled and observed.

Both conditions are satisfied or can be implemented with simple measures on the aircraft.

It is remarkable that in this connection, in spite of the great physical importance, a Φ-switching is not necessary for dynamic reasons and, therefore, the main filter problem is removed. In addition, the influence of every additional feedback, in the sense of pole definition, is compensated for by other controller branches. In general, this should lead to an increased parameter sensitivity of the system.

In general, there are severe restrictions when specifying the eigen values, if a filter is introduced into a control loop. If one considers it as a dynamic compensator, then we find the system structure shown in Figure 6. Only the nominal variables of horizontal speed v and vertical speed $\dot{h}$ are the only parameters which are integrally controlled. /266

There are various possibilities for switching in the control variables. From the transfer functions of the systems, according to control theory, we first of all can calculate a stationary uncoupling filter or one can use flight mechanical theory. For example, this was done by the DFVLR during the ZKP project "flight control" [4].

One condition is that in both cases the control loop is sufficiently fast even with the filter. Design problems can occur because the compensator denominator polynomial of ℓ-order is specified, which is used to generate the filter effect. Only a maximum of $m = \ell + r - 1$ eigen values can be specified. In the case of a PD_2T_3-filter, one pole can no longer be specified independent of the other.

5. $\dot{H}$-filtering

Basically, we have the same filter structure for the $\dot{H}$-filter as for the v filter. Nevertheless, both signals cannot be filtered together in one compensator. As can be seen from the simplified block diagram Figure 7, vertical wind disturbances are already damped by the aircraft itself in contrast to the horizontal wind perturbations. In other words, for the higher frequency range, the aircraft itself represents already a PDT_2-filter with the characteristic polynomial of the controlled α-oscillation: Any additional filtering of higher order rotates the phase in the useful frequency range so much that only small amplifications are allowable and, therefore, $\dot{H}$-switching is practically of no value.

6. Results

Since we have not specified the structure of the overall system, we will give a summary of the orders of magnitude of the improvements which might be achieved. As a reference, we considered the previously used A300 controller.

First of all, we retained the A300 autopilot while modifying the thrust control loop with a PD_2T_3-filter and a PT_1-$\dot{h}$-filter for power or energy control, respectively. For about the same degree of quiet operation under thrusting, it is already possible to sub- /267 stantially improve the maintenance of the trajectory and the path using the existing system.

Since both partial control systems are difficult to tune with respect to one another, after this we investigated an additional control loop using the structure already discussed in Figure 6. The only physical coupling variable which is required and which is sufficient from the control theory point of view between both system inputs is the vertical speed $\dot{h}$. Again, we used a PT_1-unit for $\dot{H}$-filtering and a PD_2T_3-unit for v filtering as filters.

Since linear filters can only perform separation of useful signal and perturbation signal according to frequency, in order to reduce the effects of low frequency gust components, we limited the wind gradients in the filters. The structure of the v filter is shown in Figure 8 and it is simple to realize.

Figure 9 gives a comparison of the reactions of the mentioned coupled controller system (VF controller) and the A300 controller to the New York wind shear which led to the crash of a Boeing 727. In order to allow a simplified meaningful representation, we selected

$2 \frac{m}{s}$ here as a standard deviation of the gusts, because for $3 \frac{m}{s}$ gusts, the A300 controller fails because of unfavorable coincidence of the gusts and the wind shear. In other words, it restarts because of large altitude deviations.

The altitude and path deviations especially during the critical final phase of landing approach have clearly reduced maximum values. There are substantial improvements in the thrust variation: whereas the uncoupled system runs almost from idling up to the limit with a large gradient and certainly would trigger false responses by the pilot, the VF controller still has a substantial thrust reserve of 100.000 N.

Figure 10 shows the percentage improvements of the individual systems. Since the comparison of the uncoupled control system and the coupled control system is somewhat unfavorable, we show a coupled system with a complementary filtering (I-R) which has been suggested by industry as an additional comparison. In all systems, we can notice the great improvements in the trajectory control for large gust standard deviations, such as occur in connection with extreme wind shear situations. The trajectory control can be improved by about 20%.

/268

In addition, in this coupled system (VF-R) compared with the other systems, we have even more substantial improvements in the quiet operational characteristics during thrusting, which in all cases are about 20%. If we favorably consider the poorer controller and assume that the fuel consumption increases linearly with thrust, as an additional positive boundary effect we have a fuel savings of about 10%, with simultaneously a reduced total noise load, compared with the A300 controller. These are small contributions, but they could add up fast for short distance aircraft.

As additional investigations have shown, the use of filters in the control loop does not result in any velocity losses with respect to the control behavior.

7. Summary

In order to bring about the safest possible landing approach under wind shear conditions with quiet operational characteristics during thrusting, it is necessary to separate gusts from wind shear components when designing the flight controller.

Improvements in the trajectory and path control compared with conventional control systems are possible using a perturbation variable switching or a power control of the thrust. For measurement and technical reasons, the latter method must be preferred.

The initially formulated requirements about flight operation during thrusting, the requirement on the structure and the control behavior can be satisfied with filters without rise errors, if one considers several physical and control theory fundamentals.

By limiting the wind gradient in the filter, in addition it is then possible to bring about a simple but quite effective amplitude separation of the gust components and the wind shear components in addition to the frequency separation. Further improvement in splitting off the low frequency gusts is possible, but involves clearly increased mathematical complexity. One possible solution here are the position variable controllers or the use of adaptive perturbation variable observers which are used as filters.

/269

8. References

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[3] Hohlfeld, J.: Investigation of discrete filters for wind shear measurement. SFB 58-Mitt. No. 79, 1979.

[4] Adam, V., Leyendecker, H.: Increase in the control accuracy by using an integrated, digital flight control system. Lecture No. 79-043 at the DGLR/DGON-Symposion "Flying near the Airport" April 1979 in Hamburg.

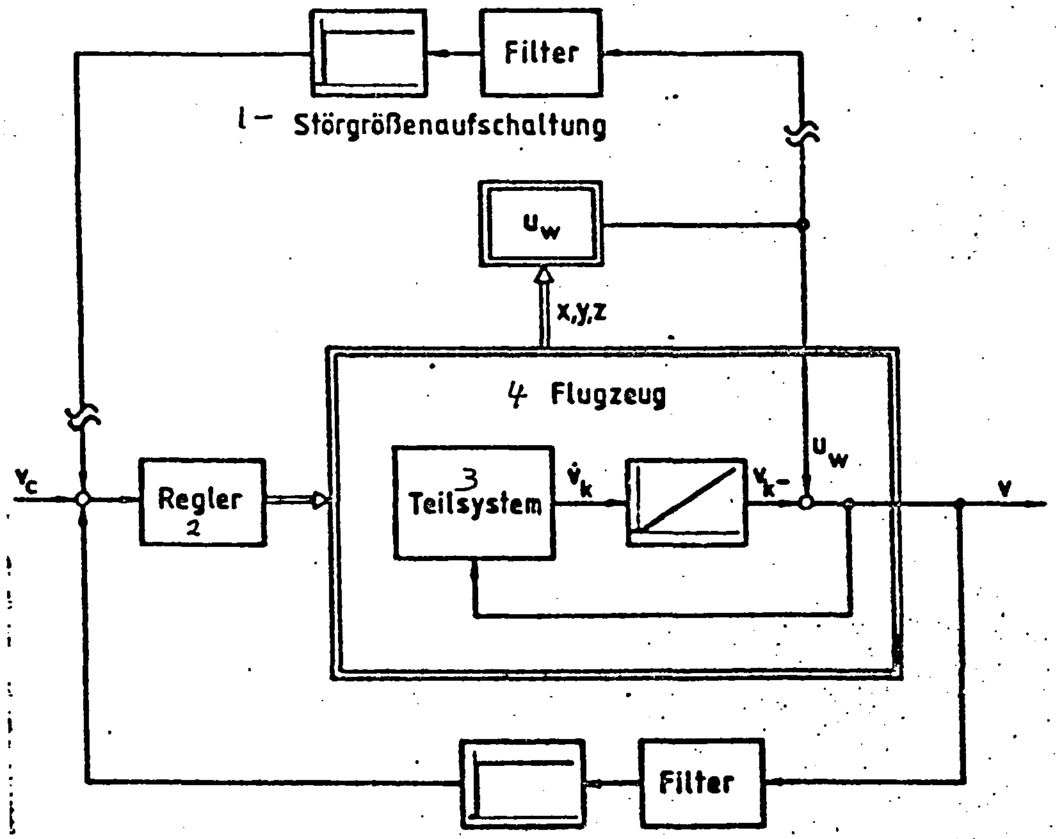


Figure 1. Simplified BSB for horizontal wind perturbations. Filter in the control loop.

1--perturbation variable switching 2--controller 3--partial system 4--aircraft

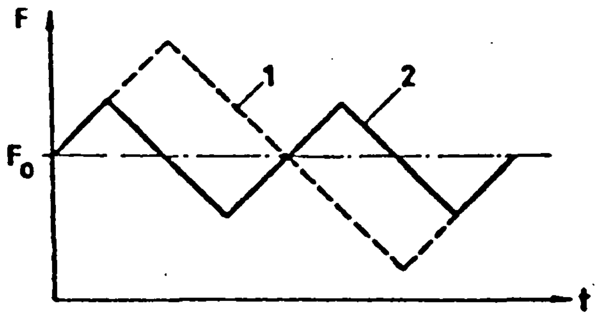


Figure 2. Evaluation of the thrust noisiness

$$\dot{F}_1 = \dot{F}_2 \quad \sigma_{\Delta\dot{F}} = \sqrt{\frac{1}{T}\int_0^T \Delta\dot{F}^2\, dt}$$

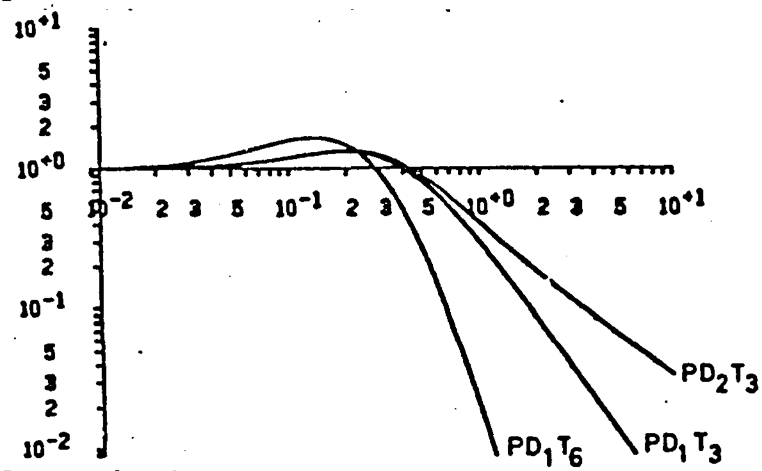


Figure 3. Amplitude variation of filters without rise error (n--multiple pole at p = -0.331)

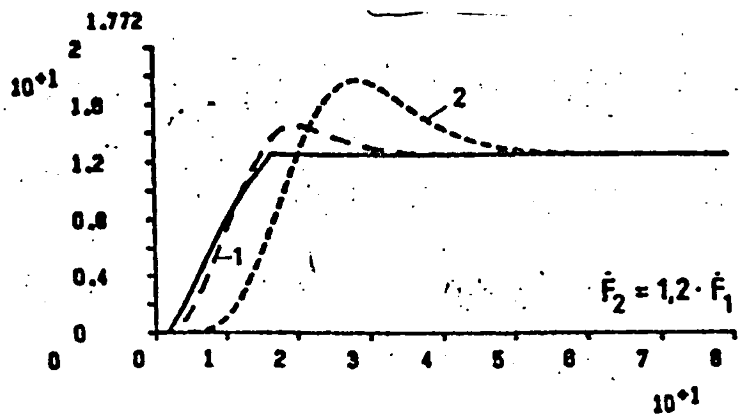
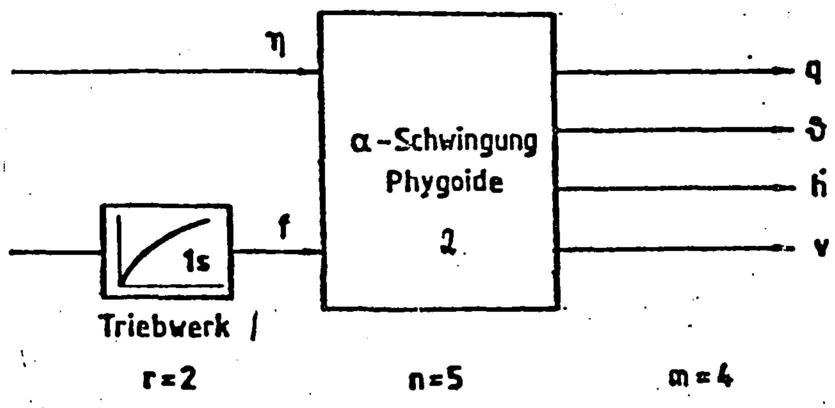


Figure 4. Ramp responses of PD_2T_3-(1) and PDT_6(2) filters



1--engine 2--
2--α oscillation phygoid

Figure 5. Linearized base system of the aircraft.

Pole specification of m+r-l(l=5) eigen values, if the system matrix is cyclical and the total system of vectors of the input and output matrices can be completely controlled and observed.

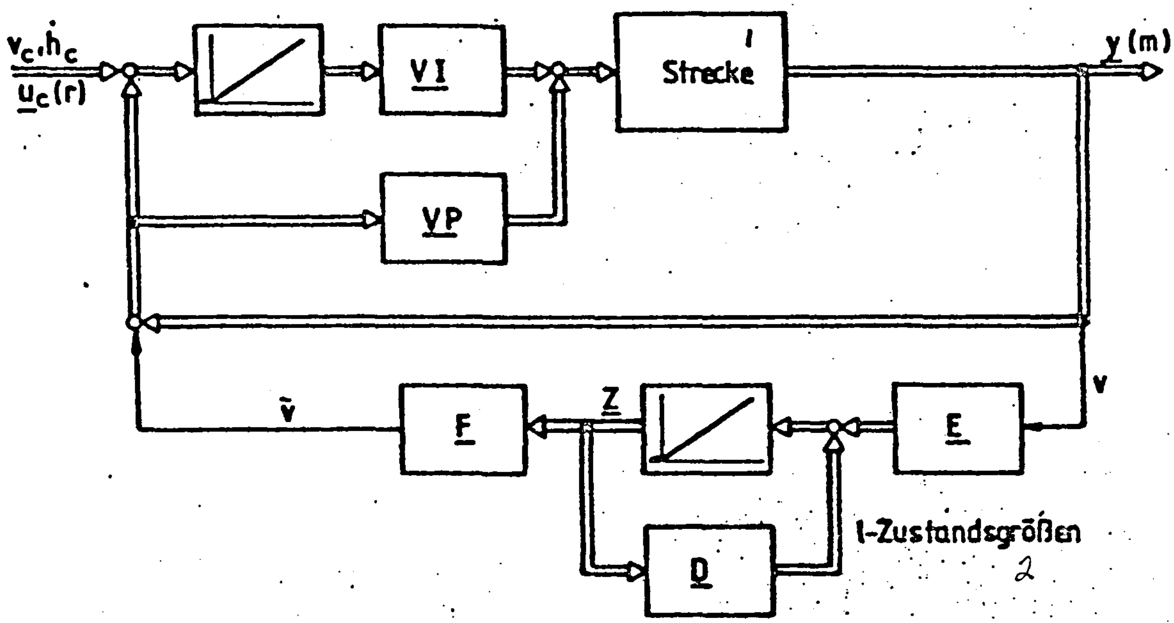


Figure 6. Control system with dynamic compensator.

For specified compensator denominator polynomial, specification of m + l + r -l eigen values

1--path 2--state variables

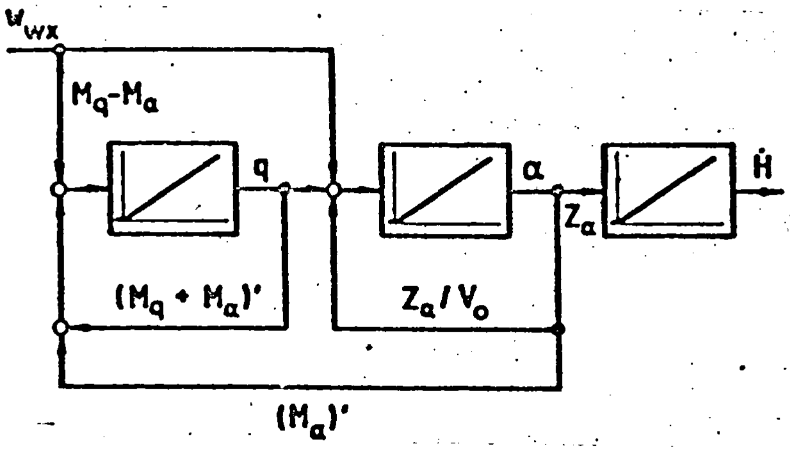


Figure 7. Filtering of w_{wx}- perturbations by the α oscillation.

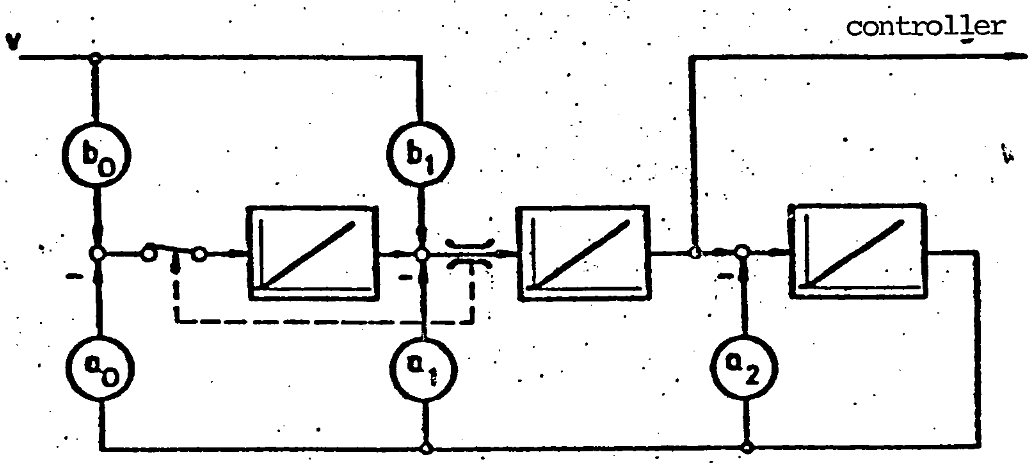


Figure 8. Control of the v-filter.

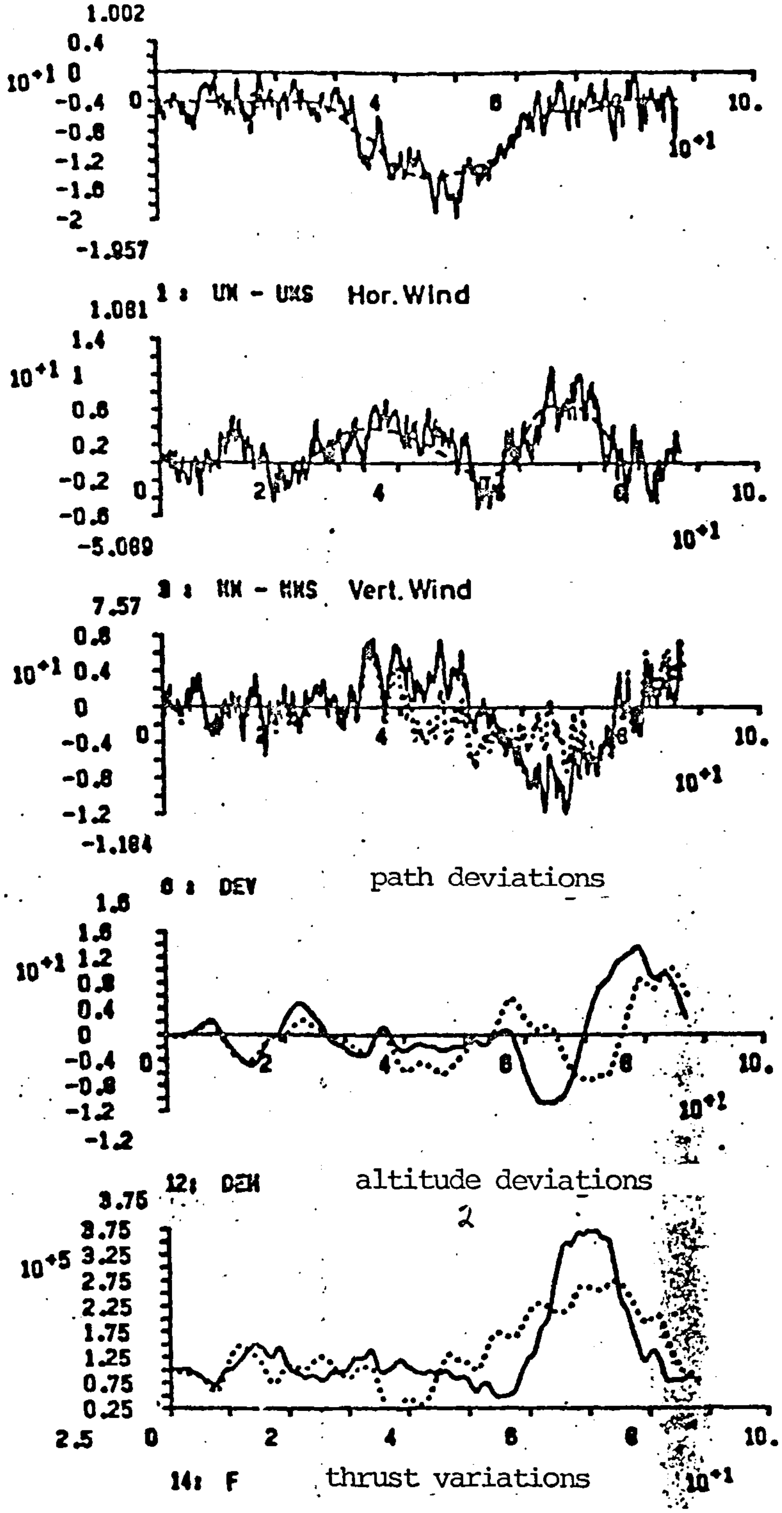


Figure 9. Comparison of A300 controller with VF control

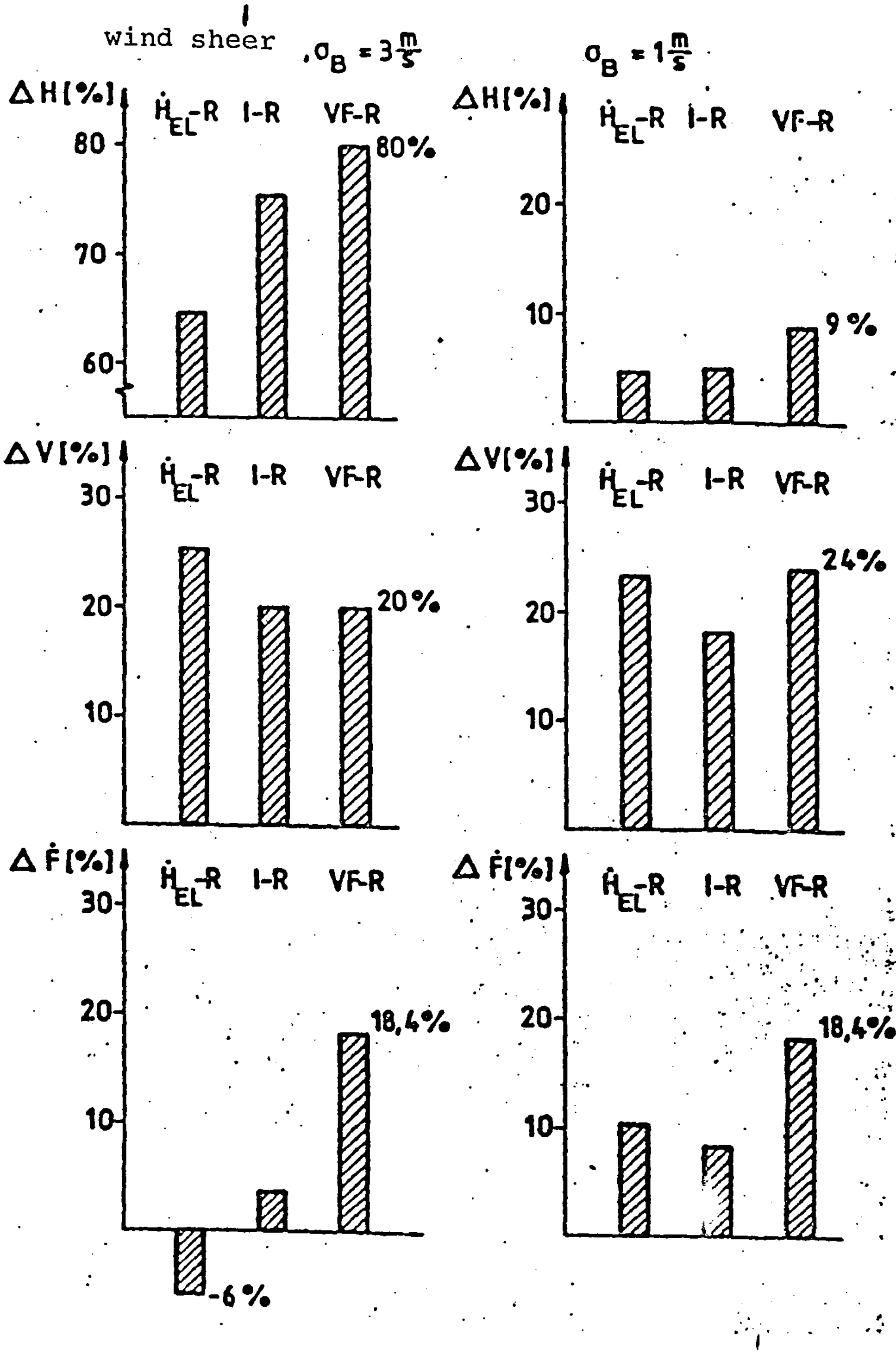


Figure 10. Improvements with respect to the previous A300 controller.

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