

HANDLING QUALITIES EVALUATION OF HELICOPTERS WITH
DIFFERENT STABILITY AND CONTROL CHARACTERISTICS

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Abstract

The intention of this paper is to present a discussion of and contribution to the evaluation of handling qualities criteria of helicopters, especially for IFR-flight. For a critical examination of helicopter flight dynamics it is necessary to consider the combination of stability and controllability. Therefore, pilot-in-the-loop methods are used.

The existing stability boundaries are considered and compared with results of closed-loop analysis. Root-locus-curves and Bode-plots in the frequency domain are applied. For a special case, a time history for a gust disturbance is plotted showing the influence of the pilot model.

1. Introduction

In the last years applications for helicopters were greatly extended. During the same period the tasks and missions for helicopters have been defined more exactly. One significant expansion of the helicopter role was the desire to use the helicopter under instrument meteorological conditions. During the 1960-1970 decade industry requested that handling qualities criteria be established for helicopters flying under IFR conditions. In response the Federal Aviation Administration (FAA) issued additional standards for helicopter IFR certification (Ref. 1). These standards correspond in many respects with the military requirements (Ref. 2). Varying from the philosophy of the airworthiness requirements previously established for helicopters flying under VFR-conditions boundaries for dynamic stability and controllability were established for the new IFR standards.

The rating of the vehicle flyability is based on the degree of cooperation between the vehicle and the pilot during the mission. The rating is therefore directly dependent on the pilot's workload. We can see from this definition that any fixed boundary established in this area will be restrictive and inflexible. Considering the many parameters which contribute to stability and, ultimately, the assessment of handling qualities by the pilot, it is unlikely that a single universally applicable numerical condition of stability and/or controllability will ever be found.

The development of rotor systems without flapping and lagging hinges yielded additional difficulties in the use of the established handling qualities criteria. Essentially the behaviour of helicopters with a hingeless or a rigid rotor differs from the behaviour of helicopters with a conventional rotor (Ref. 3). With the hingeless rotor system the dynamic stability requirements specified in the standards can't be met whereas an improved controllability is obtained. These specific variations of the system were not taken into considerations when the handling qualities criteria were developed because the criteria were based only on simulation and flight tests of helicopters which had hinged blade rotor systems.

2. Helicopter Flight Dynamics

The helicopter flight dynamics can be described by a nonlinear ordinary differential equation system of the form

$$\dot{x} = f(x, u)$$

where x is the state vector

$$x = (u_g, v_g, w_g, p, q, r, \phi, \theta, \psi)^T$$

and u the control vector

$$u = (\theta_o, \theta_c, \theta_s, \theta_{HR}, w_w)^T$$

In a trimmed flight condition the system can be linearized by computing the partial derivatives with respect to all state and control variables:

$$\Delta \dot{x} = A \cdot \Delta x + B \cdot \Delta u$$

The Laplace transformation yields

$$s \cdot \Delta X(s) = \Delta X_o + B \cdot \Delta U(s)$$

and

$$\Delta X(s) = - (A - s \cdot E)^{-1} \cdot \Delta X_o - (A - s \cdot E)^{-1} \cdot B \cdot \Delta U(s)$$

By setting

$$\det(A - s \cdot E) = 0$$

the eigenvalues of the system are derived which are the poles of the transfer function. Fig. 1 shows the poles for the longitudinal motion of helicopters with different rotor systems with the boundaries specified by military and civil criteria for IFR. The poles which characterized the phugoid mode of the helicopter with hingeless rotor are lying outside the acceptable region.

From the second term the transfer function zeros are calculated for the control variables. For a helicopter with a hingeless rotor in a trimmed flight condition with $V = 200$ km/h, the transfer function for the Euler angle θ after cancelling like terms in the numerator and denominator is

$$\frac{\theta}{\eta} = 0.039 \frac{(s + 0.805) \cdot (s + 0.047)}{(s + 6.23) \cdot (s + 0.43) \cdot (s^2 - 0.38s + 0.23)} \frac{\text{rad}}{\text{mm}}$$

η is the stick position measured at the pilot's hand where the blade cyclic pitch $\theta_s \approx 0.04 \cdot \eta$ deg for η in mm. So 1 inch pilot input to the stick results in about 1 deg in θ_s .

Fig. 2 shows the relative pitch damping versus relative pitch control sensitivity for helicopters with different rotor systems and limits as given in different sources.

3. Closed-Loop Analysis

The theoretical analysis of the pilot-helicopter system is a fruitful way to examine the handling qualities of the helicopter, especially there are no possibilities of flight testing combined with rating evaluations of pilots. The coefficients in the pilot model have a functional relationship to the pilot's workload and the pilot's rating. The pilot may be thought of as an adaptive feedback system. Corresponding to his capabilities and his training the pilot fulfils the given task. In a wide range of handling qualities the pilot can obtain

fundamentally the same mission results by changing his equalization characteristics.

In this investigation, the pilot has to stabilize the longitudinal modes. The block diagram in Fig. 3 explains the given task. On the gyro horizon the pilot compares the reference input and the feedback signal of pitch attitude. Any deviation signal he transfers in a longitudinal stick input. In reality the pilot is required to perform many other tasks simultaneously. The theoretical representation of the one-axis stabilizing task is therefore a simplification. It can be imagined, however, that an autopilot assumes all other tasks of the pilot. Closed-loop analysis of pilot-vehicle systems performed in such a way have proved very fruitful in comparing handling qualities and in predicting pilot workload and rating for a given task.

3.1 Human Pilot Transfer Function

The human pilot transfer function corresponds to the quasilinear model that has been often described in literature (Ref. 4). This model is a sufficient approach for the one-degree-of-freedom stabilization task and also meets the requirements for simplicity. The fundamental human control characteristics are adequately described for a wide range of controlled element dynamics, disturbing function amplitudes and disturbing function frequency content.

The pilot model is composed of two terms.

$$Y_P(s) = K_P \cdot \frac{1 + T_L \cdot s}{1 + T_I \cdot s} \cdot \frac{e^{-\tau \cdot s}}{1 + T_N \cdot s}$$

The last term represents the inherent reaction ability of the pilot and is considered as not to be influenced. The transport lag or pure time delay described by $e^{-\tau \cdot s}$ represents an accumulation of delays encountered in the transmission of information from the eye to the brain, decision making, and transmission of information from the brain to the muscles. The neuromuscular lag represented by the approximation $(1 + T_N \cdot s)^{-1}$ describes the lag involving in moving the wrist and arm to the commanded position after the signal arrives at the muscles. Representative values for τ are between 0,1 and 0,25 seconds and for T_N approximately 0,1 seconds.

In the first term are the factors which represent the pilot's adaption into the loop and his accomodation to the plant. Pilot gain, K_P , represents the pilot's control response to an error in the magnitude of a controlled variable. The lead term, $(1 + T_L \cdot s)$, is an indication of the pilot's control response to the rate of change in the error of the controlled variable. In the same way the pilot can use a lag term, $(1 + T_I \cdot s)^{-1}$, if this is necessary to achieve the desired system response. These adaptive coefficients depend on the controlled element and the flight conditions. Of course in addition the pilot's training and his concept about the mission also influence the model. Non-linear models have been developed for special investigations, Ref. 5. These models are very complicated and there are no essential improvements expected by their application to flight mechanics problems like this one.

3.2 Pilot Rating

The assumption is made that the pilot workload and the subjective pilot rating is functionally related to the characteristics of his transfer function. To handle multi-axis tracking situations, it is assumed that pilot rating (decrement relative to optimum) for each axis can individually be calculated then summed up to an overall rating. For the investigated task the functional connection is defined as:

$$PR = (PR)_O + \Delta PR_{K_P} + \Delta PR_{T_L} + \Delta PR_{T_I} + \dots$$

The $(PR)_O$ term may be thought of as a pilot bias which is influenced by his experience, the characteristic of the instrumental equipment and the pilot's concept of the aircraft behaviour desired for the mission being flown.

The last three terms represent the incremental rating for the gain, lead time and lag time. As an example, the influence of pilot gain on pilot rating can be seen from Fig. 4. It is important to note that acceptable optimum pilot gain exists, $K_P \approx 250$ mm/rad (Ref. 4, 6). For pilot gains either larger or smaller than the optimum, the pilot rating deteriorates. In this case the pilot finds the aircraft to be too sluggish or too sensitive respectively.

The pilot attempts to control the aircraft as far as possible with his gain only. He prefers to operate without a lead and/or a lag time. He accepts a lead time constant when needed to stabilize the system and/or to compensate for his own time delay and neuromuscular lag. For T_L less than about 0,4 sec there is only a little change in rating, whereas for T_L greater than 0,4 sec there is a roughly linear decrement in rating with increasing T_L (Fig. 5). The pilot perceives a large change of a lead time as being more complicated and requiring more workload than if he changed his gain. Pilot generated lags seem to be much more tolerable and, therefore, increases in T_I as high as 4 sec influence the rating only slightly.

3.3 Closed-Loop Considerations for Pitch Closure

The inherent values of the pilot that were used in the pilot function are

$$\tau = 0.25 \text{ sec} \quad \text{and} \quad T_N = 0.1 \text{ sec}$$

The average pilot has a smaller delay time constant (τ), however, the high value was preferred for a worst case study. Pilot model was linearized for the computation by using a first-order Padé approximation for the pilot's transport lag term. An adaptive lag time wasn't taken into considerations, because an one-axis stabilization task may be considered as having no lag time. The final selected model was of the form

$$Y_P(s) = K_P \cdot (1 + T_L \cdot s) \cdot \frac{1 - 0.125 s}{1 + 0.125 s} \cdot \frac{1}{1 + 0.1 s}$$

The pilot adjusts his equalization parameters such that stable control is achieved. Furthermore it was assumed, that the pilot-helicopter closed-loop dynamic response is similar to the response one would obtain by employing the known performance criteria for linear control systems. In this case the performance criteria are based upon the minimization of the integral of time weighted error functions of the controlled variable.

Fig. 6 to 8 show the root locus curves of the closed-loop systems of helicopters with different rotor systems and a flight velocity of about 200 km/h (Ref. 7). The shape of the curves are similar for the helicopter with an articulated rotor and the helicopter with a see-saw-rotor. A pilot can stabilize the helicopters in an acceptable way; he does not have to employ any lead time and the values of the pilot gains ($K_P = 250$ mm/rad and $K_P = 220$ mm/rad) are in the comfortable region. The decrements of the pilot ratings are negligible and the pilot workload is acceptable for the stabilization task.

The evaluation of the handling qualities of a helicopter with hingeless rotor is more complicated because the results of closed-loop analysis are quite diverse. The pilot can close the loop by combining his adaptive coefficients in two ways without exceeding the comfortable region of his equalization coefficients. In first way there exists one oscillation, if the pilot controls the helicopter with a gain of $K_P = 320$ mm/rad and a lead time of $T_L = 0.2$ sec. The second way results in two oscillations when the pilot combines $K_P = 350$ mm/rad with

$T_L = 0.3$ sec. Both of these combinations of the adaptive coefficients result in similar pilot rating, that value is about $\Delta PR = 0.1$.

Fig. 9 shows the Bode plots of the system consisting of a pilot and a helicopter with hingeless rotor. For good system performance the crossover frequency, ω_c (defined from the Bode plot as the highest frequency intersection with the zero-db line) must be at least as large as the input disturbance bandwidth. For automatic or manual control, it is desirable that near ω_c a broad K/s-like region exists. On the other hand, adequate gain and phase margins (K_m about 6 db and ϕ_m about 30°) are necessary to insure nominal stability. The information obtained from interpreting the Bode plots yields the same results discussed previously in conjunction with the root-locus technique. The pilot overcomes the instability in the phugoid mode of helicopters with hingeless rotors with help of the better controllability. The workload required to stabilize the various helicopters differs only in a small region and the pilot will rate the helicopters as satisfactory for the stabilizing task.

3.4 Pilot Gain Approximation

For a simplified calculation of the influence of pilot control on system stability the following approximations are made at low frequencies

$$\frac{\eta}{\theta} = K_P \cdot \frac{1 + T_L \cdot s}{1 + T_N \cdot s} \cdot e^{-\tau \cdot s} \approx K_P \cdot (1 + T^{**} \cdot s)$$

with

$$T^{**} = T_L - T_N - \tau$$

The dynamics for the helicopter with hingeless rotor can be approximated by

$$\frac{\theta}{\eta} = + K \frac{s}{s^2 + 2\zeta \cdot \omega_n \cdot s + \omega_n^2}$$

where

$$K = \frac{0.039}{6.23} \frac{\text{rad}}{\text{mm} \cdot \text{sec}}, \quad 2\zeta \cdot \omega_n = -0.38 \text{ sec}^{-1} \quad \text{and} \quad \omega_n^2 = 0.23 \text{ sec}^{-2}$$

The characteristic equation after loop closure becomes

$$(1 + K \cdot K_P \cdot T^{**})s^2 + (2\zeta \cdot \omega_n + K \cdot K_P)s + \omega_n^2 = 0$$

For

$$T_L = 0.40 \text{ sec}, \quad T_N = 0.10 \text{ sec}, \quad \tau = 0.25 \text{ sec}$$

one obtains $T^{**} = 0.05$ sec which can be neglected, so the natural undamped frequency of the phugoid mode is not altered.

The new damping factor is

$$\xi_{\text{new}} = \xi + \frac{K \cdot K_P}{2 \omega_n}$$

which yields with $K_P = 200$ mm/rad

$$\xi_{\text{new}} = 0.90$$

In comparison, the exact calculations for the root locus yielded only a value

$$\zeta_{\text{new}} = 0.63$$

but, although the damping factor is too high, the simplified approach gives a hint on the influence of pilot gain, K_p , and lead time, T_L , on the low frequency dynamics.

A high value of gain, K , is good for the stabilization task. Because

$$K \approx \frac{M_n}{M_q}$$

one obtains the same effect by a large M_n and/or a low M_q . On the other hand, the assumption for the approximation is not valid if M_q is too small.

3.5 Influence of Gusts

To see the influence of the pilot on gust response, time history plots were calculated for the helicopter with hingeless rotor. It was assumed that a gust velocity of 1 m/s in vertical direction beginning at $t_i = 0.1$ sec and ending at $t_f = 4.0$ sec disturbs the helicopter flight path.

When the pilot does not control the helicopter, then the phugoid mode is excited. From the eigenvalues of the system we get

$$\sigma = 0.19 \text{ sec}^{-1} \quad \text{and} \quad \omega = 0.44 \text{ sec}^{-1}$$

which gives values of

$$T = 14.2 \text{ sec} , \quad t_D = 3.6 \text{ sec} \quad \text{and} \quad \zeta = -0.40$$

The time history for the Euler angle θ is shown in Fig. 10. When the pilot is in the control loop, the motion is damped.

For the following values of the pilot model parameters

$$K_p = 200 \text{ mm/rad} , \quad T_L = 0.40 \text{ sec} , \quad T_N = 0.10 \text{ sec} \quad \text{and} \quad \tau = 0.25 \text{ sec}$$

from Fig. 6 the phugoid has values of

$$\sigma = -0.66 \text{ sec}^{-1} \quad \text{and} \quad \omega = 0.82 \text{ sec}^{-1}$$

which yields

$$T = 7.6 \text{ sec} , \quad t_H = 1.05 \text{ sec} \quad \text{and} \quad \zeta = 0.63$$

Higher frequency roots are well damped and are not considered here. The time history of parameters for this pilot-in-the-loop model have also been calculated. The plot for the Euler angle θ (Fig. 11) shows a damped motion which is already very small after a time of only 10 sec. The necessary stick motion is also shown.

4. Conclusions and Future Aspects

The decrements of pilot ratings due to the stabilization work that has been done by the pilot are in the same dimensions for all types of helicopters discussed. The pilots are able to stabilize the helicopters in an acceptable way and the closed-loop analysis with a pilot model shows good dynamic response. The most important result of this paper is the demonstration that applying the present handling qualities criteria to helicopters with a hingeless rotor yields incorrect ratings. The closed loop analysis combines both the criteria for stability and controllability plus includes the requirements for a given task.

Future activities may consider an expansion of the pilot's task and involve other flight conditions for specific helicopter missions. Further, the closed-loop method is suitable for estimating the handling qualities of new concepts for rotating wing systems and of configurational studies in a more objective way. The future investigations are planned in cooperative programs between the DFVLR and MBB.

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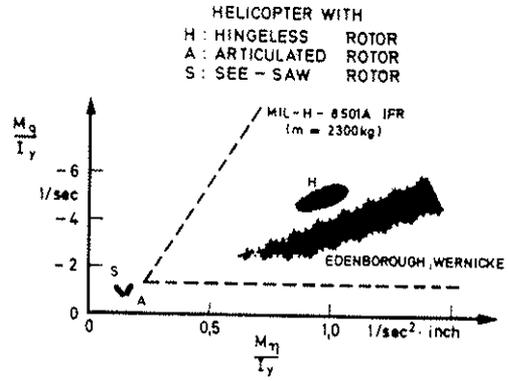
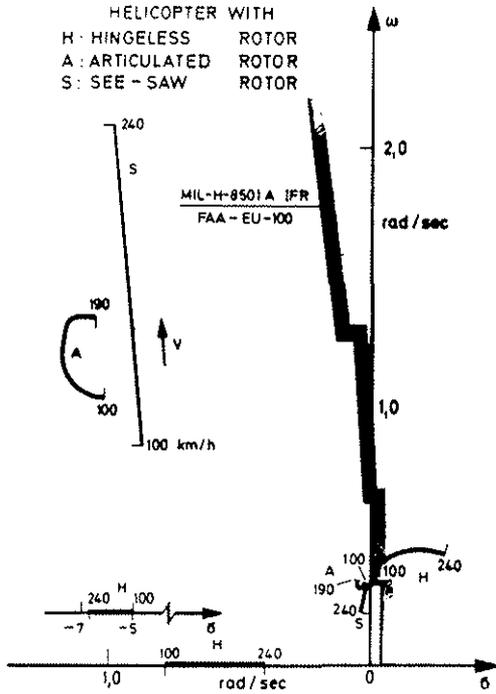


Fig. 2 Relative pitch damping M_q/I_y versus relative control sensitivity M_{η}/I_y

Fig. 1 Longitudinal dynamics criteria and poles of helicopters with different rotor systems

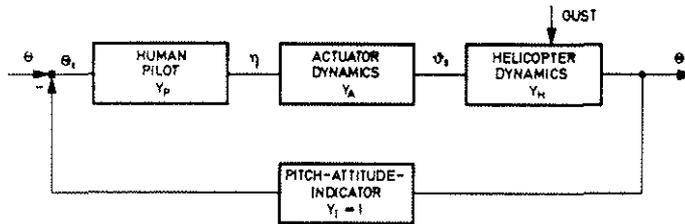


Fig. 3 Typical single-axis pitch control system

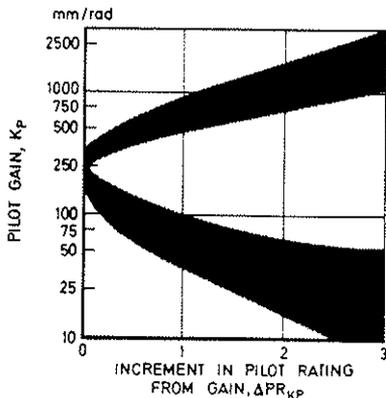


Fig. 4 Effect of gain on pilot rating

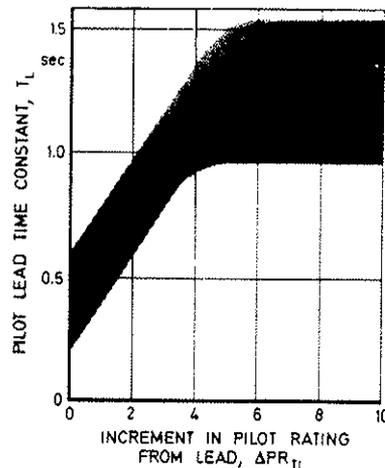


Fig. 5 Effect of lead on pilot rating

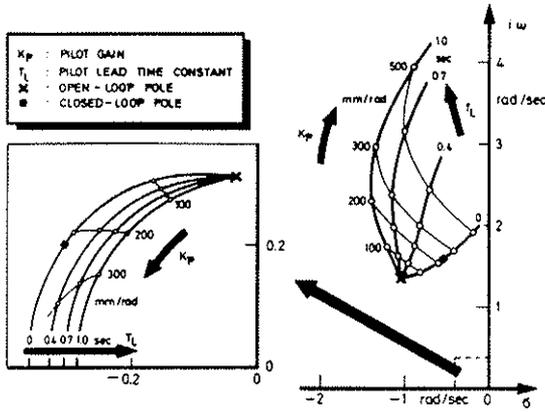


Fig. 6 Dynamic stability of the closed-loop system; helicopter with articulated rotor

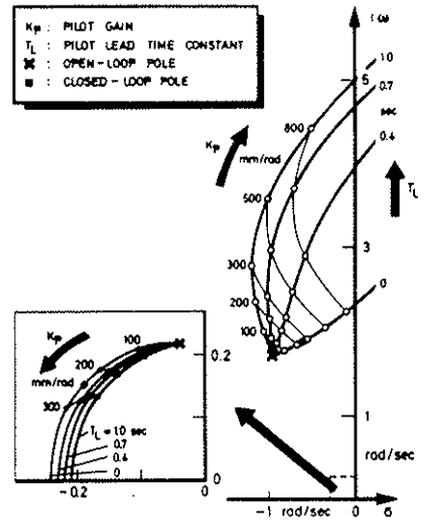
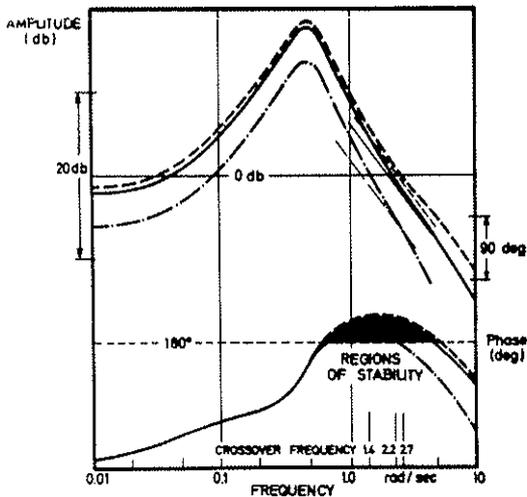
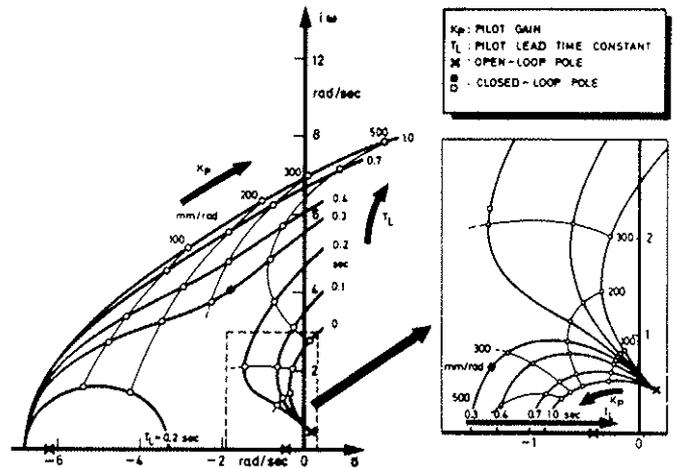


Fig. 7 Dynamic stability of the closed-loop system; helicopter with see-saw rotor

Fig. 8 Dynamic stability of the closed-loop system; helicopter with hingeless rotor



- PILOT GAIN 350 mm/rad
PILOT LEAD TIME 0.3 sec
- PILOT GAIN 320 mm/rad
PILOT LEAD TIME 0.2 sec
- PILOT GAIN 200 mm/rad
PILOT LEAD TIME 0 sec

Fig. 9 Bode plots of the system pilot/helicopter with hingeless rotor

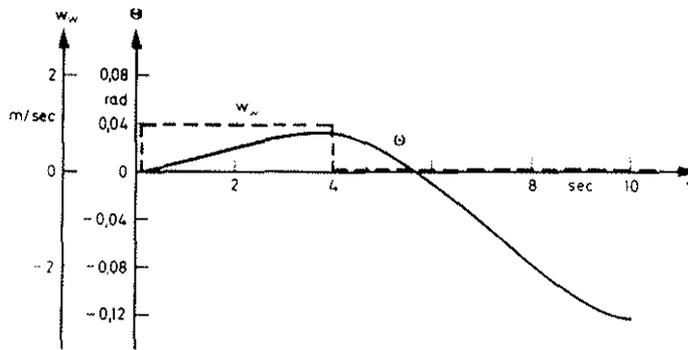


Fig. 10 Pitch attitude time response, θ , with gust disturbance, w_w

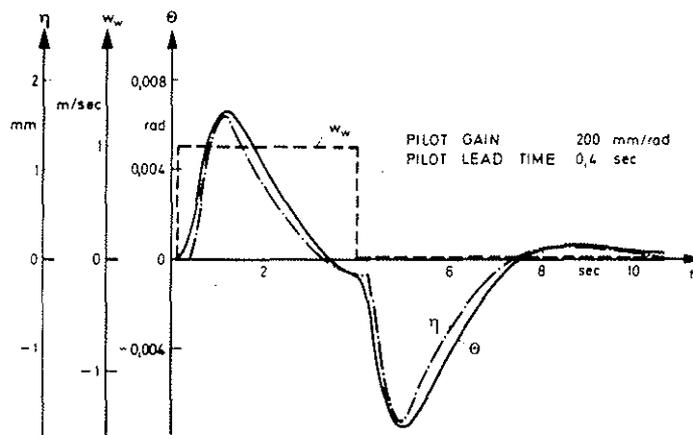


Fig. 11 Pitch attitude time response, θ , and stick position, η , with gust disturbance, w_w (closed-loop)