Engineering Notes

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Control Surface Pumping—A Pilot's Technique for Controlling the Flight Path Precisely

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Introduction

THE longitudinal control surface is pumped rapidly during the last few seconds of a landing by many pilots; the amplitude and rate of the pumping motion vary with airplane design. This control pumping motion is of interest since the maximum control surface rate requirement imposed on the normal and emergency control system is dictated by this control usage. If the required control surface rates are not made available, landings may be aborted occasionally because of a "locked control"† when the pilot unconsciously pumps the control, or a large pilot population will have been prevented from flying the machine in the most optimum manner.

Although control pumping manifests itself most frequently during the landing flare of a fighter-type aircraft, it also may be experienced during other precision control tasks (i.e., formation flying, in-flight refueling, etc.) and with other types of aircraft. This paper analyzes the pumping phenomenon and presents a method for predicting the frequency and amplitude of the control pumping motion to be experienced with a given aircraft design.

Although this study was conducted many years ago, it is presented at this time for the following reasons. To the author's knowledge, the control pumping phenomenon is to this date not covered in the literature. Also, the results of this study were the basis of the precision control theory,[1] which has been substantiated in recent years by flight and moving-base simulator tests.

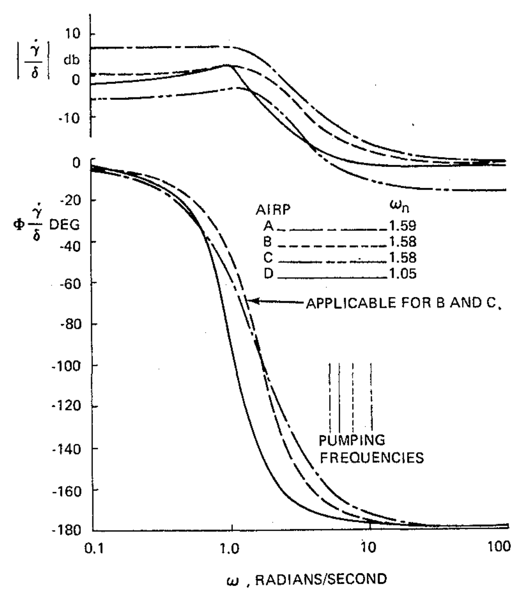

Fig. 1 Frequency response in rate of change of flight path angle for various aircraft in the landing configuration.

Analysis

The rapid pumping of the horizontal control surface occurs only during the terminal phase of the landing. At no time is the control pumped when practice landings are performed a great distance above the ground. It is, therefore, reasonable to assume that the pilot seeks additional information and control capability as the airplane approaches the ground and that these desires are fulfilled as a result of pumping the control.

Flight-test records of stick and control deflection obtained during landing flareouts showed the pilot-induced pumping motion to be closely simulated by a sinusoidal input superimposed on a ramp input. It was thought, therefore, that the information the pilot sought by pumping the control could be directly determined by examining the frequency response characteristics of some airplanes that are pumped.

The airframe frequency response characteristics in $\dot\gamma$ (proportional to load factor), $\dot\theta$ and $\ddot\theta$, to horizontal control inputs, were calculated for four airplanes using the following transfer functions, are presented in Figs. 1–3, respectively:

$$\dot\theta/\delta = K_\theta(TP + 1)/(P^2 + 2\zeta\omega_n P + \omega_n^2)$$

$$\ddot\theta/\delta = P(\dot\theta/\delta)$$

$$\dot\gamma/\delta = K_\gamma(P^2 + bP + c)/(P^2 + 2\zeta\omega_n P + \omega_n^2)$$

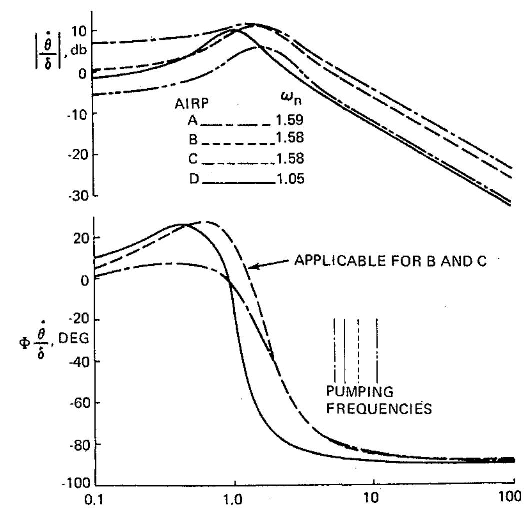

Fig. 2 Frequency response in angular velocity for various aircraft in the landing configuration.

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† A case of the pilot "pushing oil" because of inadequate power boost flow rates.

Table 1 Angular acceleration values generated by control pumping on various airplanes

Airplane	Average control amplitude, deg	$\lvert\ddot{\theta}/\delta\rvert$ 1/sec²	$\ddot{\theta}$ deg/sec²
A	$\pm$ 1.0	6.4	6.4
B	$\pm$ 2.4	2.5	6.0
C	$\pm$ 1.3	5.1	6.6
D	$\pm$ 2.9	2.3	6.7

where

$$\omega_n^2 = -M_\alpha - L_\alpha M_q$$

$$\zeta = (L_\alpha - M_q - M_{\dot{\alpha}})/(2\omega_n)$$

$$K_\theta = K_\gamma = (C_{L_\alpha} C_{m_\delta} - C_{m_\alpha} C_{L_\delta})/[(-mV/\bar{q}S)C_{m_\alpha} - (\bar{c}/2V)C_{L\alpha}C_{m_q}]$$

$$T = [(mV/\bar{q}S)C_{m_\delta} - (\bar{c}/2V)C_{m_{\dot{\alpha}}}C_{L_\delta}]/(C_{L_\alpha}C_{m_\delta} - C_{m_\alpha}C_{L_\delta})$$

$$b = -M_{\dot{\alpha}} - M_q$$

$$c = M_\delta(C_{L_\alpha}/C_{L_\delta}) - M_\alpha$$

defined as

$$M_\alpha = (\bar{q}S\bar{c}/I_y)C_{m_\alpha} \qquad M_q = (\bar{q}S\bar{c}/I_y)(\bar{c}/2V)C_{m_q}$$

$$M_\delta = (\bar{q}S\bar{c}/I_y)C_{m_\delta} \qquad M_{\dot{\alpha}} = (\bar{q}S\bar{c}/I_y)(\bar{c}/2V)C_{m_{\dot{\alpha}}}$$

$$L_\alpha = (\bar{q}S/mV)C_{L\alpha}$$

The average frequency at which the pilot pumped the control and the aircraft natural frequency also are indicated in these figures. (The pumped frequency for airplane D, however, was obtained after this study was conducted.)

These data show that the control is pumped by the pilot at a frequency that is considerably above the natural frequency of the airframe. At these pumping frequencies, the airplane response in $\dot{\gamma}$ is negligible whereas the response in $\ddot{\theta}$ is close to the maximum value attainable. A minimum phase shift (in the order of 10° or less) also is realized between $\ddot{\theta}$ and the control surface deflection at these high pumping frequencies. If the control system has acceptable resolution, the control stick deflection is correspondingly in phase with the resultant $\ddot{\theta}$. The point to be emphasized is that higher magnitudes of $\dot{\gamma}$ and $\dot{\theta}$ per unit control input could be obtained, which would also be more in phase with the control input, at considerably lower pumping frequencies than those employed by the pilot. It appears, therefore, that the pilot desires to excite the airplane in pitch, which he accomplishes by sensing the angular pitching acceleration without disturbing the airplane flight path.

Based on the data presented herein, it appears that the control of a given design will be pumped at the frequency that approaches the minimum attainable phase shift between angular acceleration and the corresponding forcing function. If the amplitude ratio, $\lvert\ddot{\theta}/\delta\rvert$, is calculated for this frequency and divided by the human threshold of perception of angular acceleration, the amplitude of the pumping motion can also be predicted. From the data presented in Table 1, it appears that this threshold of perception value is approximately 6.5°/sec². This threshold value is considered valid since it is based on flight-determined data involving various pilots flying airplanes of different designs. In this respect it should be appreciated that this study was conducted using recorded flight-test data that were obtained by a considerable number of pilots flying different aircraft over a period of many years. In no instance were the flight test recordings obtained specifically and systematically for the investigation of the control surface pumping phenomenon. Also, the computed frequency response characteristics are within the

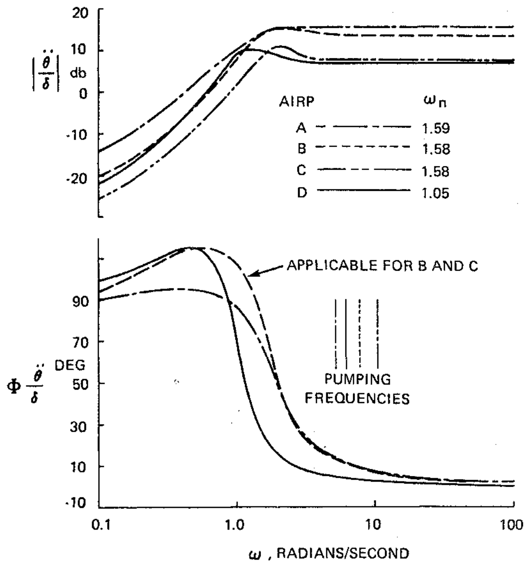

Fig. 3 Frequency response in angular acceleration for various aircraft in the landing configuration.

accuracy of the estimated aerodynamic coefficients and the flight-test-noted mass characteristics (center of gravity, weight, and inertia). In light of this nonresearch type of information, the consistency of the observations derived from the analysis presented herein is considered quite remarkable.

Also, based on this study it was predicted during the design phase of airplane D that the control surface would be pumped on this aircraft at a frequency above 4 rad/sec and at an amplitude of ±2.8°. It was also recommended that allowance be made for bypassing the stick damper in the landing mode so as not to restrict the pilot in his pumping action. The experimental flight article was pumped at a frequency of 6.29 rad/sec and at an amplitude of ±2.9°. The pilots also concurred with the recommendation for bypassing the stick damper.

Concluding Remarks

The consistency of the study results and the ability to predict the control pumping characteristics of an aircraft during the preliminary design phase are taken as an indication of the overall correctness of the following remarks. 1) The control surface is unconsciously pumped during the terminal phase of a landing at a frequency that results in a) the maximum angular acceleration per unit control input, b) the minimum attainable phase shift between the control input and corresponding pitch acceleration, and c) a negligible change in flight path angle (normal acceleration) and at an amplitude that generates an angular acceleration of 6.5 deg/sec². 2) The frequency and amplitude of the pumping motion to be encountered in operation can be predicted, therefore, during the design phase by calculating the frequency response characteristic of the aircraft in angular acceleration and applying the previous criterion (i.e., at the frequency that results in a minimum phase shift, divide the corresponding gain in the amplitude ratio, $\lvert\ddot{\theta}/\delta\rvert$, by 6.5 to obtain the control amplitude).

We have identified when and how the control is pumped. The question remaining is, of course, why? Since control pumping does not improve the physical response of the airframe, it must be deduced that the pilot is constantly sampling and employing the aircraft response in angular acceleration as a means of reassuring himself in the "goodness" or "solidness" of the airframe response to his control commands. It was stated in Ref. 1 that when a perceptible level of angular acceleration (anticipatory cue) does not precede a desired change in flight path, the pilot cannot perform that precision control task. Let us assume, therefore, that a pilot, for any one of many reasons, desires to control his aircraft flight path more precisely than normally would be required and that for these small changes in load factor the anticipatory angular acceleration cue generated falls below his threshold of perception. At this point, he can pump his control at an amplitude and frequency that will generate the required level of angular acceleration that will be in phase with his control stick inputs. That is (in servomechanism terminology), control pumping is a control technique through which the pilot can increase the gain in his lead (angular acceleration) network without driving the man-machine control loop unstable and in this manner can perform fine vernier-type of control of the flight path. Control pumping, therefore, should not be prevented or discouraged by limiting control surface rates or high stick forces.

Reference

[1] Bihrle, W., Jr., "A Handling Qualities Theory for Precise Flight Path Control," AFFDL-TR-65-198, June 1966, Air Force Flight Dynamics Lab., Wright-Patterson Air Force Base, Ohio.

A New Economic Flexible Nozzle for Supersonic Wind Tunnels

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THE design of the Nationaal Lucht-en Ruimtevaartlaboratorium (NLR) supersonic wind tunnels was guided by the requirement to achieve a maximum of testing capability at minimum cost. From this guide line followed a series of specific goals which were realized as summarized in Ref. 1. Special attention has been given to the design of the flexible nozzle.

This nozzle was applied to the 1.2×1.2 m² supersonic wind tunnel (SST) with the Mach number range $1.2 \leq M \leq 4.0$ and to the almost continuously running 27×27 cm² research tunnel (CSST) up to $M \leq 6$.

1 Basic Design Considerations

The costs of supersonic wind tunnels with continuously variable nozzles are determined mainly by the test section dimensions and the length of the nozzle. Since the construction of wind-tunnel models is costly and time consuming, it is desirable to use the same model for the complete Mach number range. With increasing Mach number the test section height can be smaller for a given model size. The highest attainable Mach number determines, for a given test section height, the length of the nozzle. It also determines the maximum run time with a given pressure in a given reservoir. Thus, with a given reservoir and model size, a variable test section height has the following advantages: shorter nozzle, lower investment, longer run time, and lower operating costs.

The simplest type of adjustable nozzle was proposed in the early fifties by Rosén.[2] The basic concept incorporated in the NLR design is shown in Fig. 1. In order to achieve the desired flow qualities for industrial type tests, this design was modified at some essential points, the results being indicated in Fig. 2a.

The Rosén design consists of contoured throat blocks mounted on pivot arms. Flexible plates are attached to the throat blocks, ending in almost parallel sections (test section plates), which form top and bottom of the test section (see Fig. 1). Symmetric rotation of the pivot arms changes the throat height and thus the test section Mach number. Dependent on the location of the pivot point with respect to the throat block, the nozzle plate length, and the choice of the plate thickness profile, an exact parallel flow can be obtained at a single Mach number. Further optimization through the complete Mach number range could only be achieved by variation of the aforementioned parameters. Without that, for a tunnel to be used in industrial development work, the resulting flow quality and the uncertainties involved are not acceptable.

The Rosén design was modified to cope with the previously mentioned problems. The most important addition was the possibility to make the length of the curved part QB, of the flexible plate PB, variable (Fig. 2a). Furthermore flexible plates of constant thickness supported by a small number of hydraulic jacks are used instead of tapered flexible plates. Also the test section height was made adjustable. Through these measures the required adjustments for parallel flow can be calculated and if necessary corrected after calibration.

Changes in length of the curved section of the flexible plate are effected by fixing the plate at the desired point Q to the flat side of the pivot arm by means of simple clamps (Fig. 2a). The nozzle section between the end of the contoured throat blocks and point Q is then flat so that up to that point radial flow condition exists.

The pressure on the outside of the flexible plates is equal to the plenum chamber pressure; therefore the pressure difference across the plates increases gradually in the upstream direction. By properly selecting the distances between the supports, the deflections due to the pressure difference can be made equal. The selection of the deflection (chosen here was $\epsilon \leq 0.01°$) then determines the plate thickness. (For all surfaces exposed to the flow, a manufacturing tolerance of $\epsilon_w < 0.025°$ was prescribed).

The space outside and ahead of the adjustable throat blocks is connected to the settling chamber. There is a pressure seal attached to and moving with the throat block (Fig. 1). It is positioned such that the forces and moments on the throat blocks are minimum and the assembly is kept relatively light.

In order to achieve the desired test section height and to compensate for the boundary-layer displacement effect, the test section plates are adjusted with two hydraulic jacks (Fig. 2a).

Several conditions incorporated in the aerodynamic design are listed below. The indices t and m refer to throat and test section.

1) The inside surface of the pivot arm and the tangent to the nozzle contour at P are both at an angle $\vartheta(M)$ with respect to the tunnel center line, (Fig. 2a). For $M_m = 4$, this angle is $\vartheta(4) = 8°$ and for $M_m = 1$ (hypothetical case) $\vartheta(1) = 0°$.

2) The curvature of the nozzle block varies linearly with x and satisfies the following conditions: first, at $P(x = 0)$, $y''(P) = 0$, $y'(P) = |\vartheta(M)|$, and $y(P) = 0$; and second at the

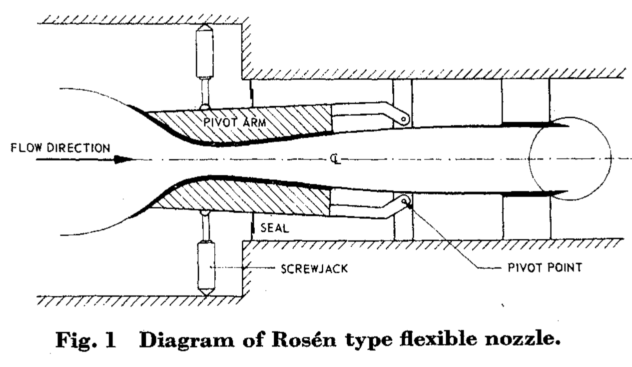

Fig. 1 Diagram of Rosén type flexible nozzle.

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