Control-Power Usage for Maneuvering in Hover of the VJ 101 Aircraft

J. SCHAEFFLER,* H. ALSCHER,* AND G. STEINMETZ*
Vereinigte Flugtechnische Werke GmbH., München, Germany
AND J. B. SINACORI†
Northrop Corporation, Norair Division, Hawthorne, Calif.

For a number of flight maneuvers that are typical for hover operation, flight-test data of the VJ 101 C X1/X2 aircraft and of a hover-rig were analyzed. All three vehicles were similar in thrust geometry and mass distribution but partly different in effective aerodynamic shape. They all used the same principles of control and type of control system for hovering operations. The hover-rig was flown both in rate and attitude modes of control, whereas the airplanes were flown in attitude-mode control only. On the VJ 101 X2, thrust modulation of afterburning engines was used for control. The flight tests were conducted under visual flight rules (VFR) conditions, with wind less than 15 knots. The results show that the mean values of control-power usage for the different maneuvers analyzed are in their relation basically similar for hover-rig and airplanes. In most of the cases vertical takeoff or vertical landing require the highest value of control power. A comparison of angular acceleration usage and pilot control action for an attitude-demand and rate-demand type of control shows a slight advantage for attitude-demand control. The influence of vehicle weight on maximum control power used seems to follow different trends for the pitch axis and roll-yaw axes, respectively. The pitch-axis results do not show an influence of weight; whereas in roll and yaw, the maximum control power used decreases with weight. The frequency contents of pilot inputs do not seem to differ from aerodynamic flight and there is no obvious influence of mode of control. Correlation of pilot's inputs as well as autopilot's inputs in pitch and roll is rather low. Finally, the handling-qualities recommendations for hover control are reviewed in the light of these results.

1. Introduction

WITH a number of VTOL configurations flight-tested, it seems worthwhile to reappraise VTOL-handling-qualities recommendations before the first generation of operational VTOL systems is leaving the design stage. This process of revision and expansion ought to be based on actual experience gained by analysis of flight data; and, for the different vehicles, it would be highly desirable to do it in a way that allows the comparison of data from different sources.

Within the general topic of handling-qualities recommendations, the design guidelines for control powers have been a point of much controversy in the past. This is understandable when one bears in mind the strong influence that maximum control power has on design thrust margin. Especially for jet VTOL aircraft, where VTO-design weight for a given mission strongly depends on the installed thrust margin, excessive control-power requirements will result in substantial weight penalties; and as the various VTOL designs differ in their sensitivity to this effect, this may also introduce a strong bias in the comparison of different designs for the same mission. Therefore, there is an imminent need for the development of methods for the reliable estimation of control powers necessary for control and trim in hover and transition, given the type of mission, the environmental conditions, and the type of configuration.

In this paper we present the results of an analysis of control-power usage for different flight maneuvers in hover from flight tests conducted with three vehicles of the VJ 101 development program. These results are necessarily in some aspects specific for the type of configuration tested, but there are also results that are independent of configuration.

Presented as Paper 66–816 at the AIAA Military Aircraft Systems Meeting, Dallas, Texas, October 18–19, 1966; submitted November 14, 1966; revision received May 8, 1967. The work was carried out under a subcontract of Entwicklungsring Süd GmbH., Munich, Germany. [7.06]

* Diplom-Ingenieur, Flight Dynamics Department, Entwicklungsbüro Munich.

† Senior Engineer.

2. The VJ 101 C Concept and Its Development

2.1. Design Features

The VJ 101 C concept featured four new ideas: 1) use of all cruise thrust for generation of lift in hover; 2) use of cruise engines with afterburning for generation of propulsive and lift thrust, avoiding the problem of deflecting the reheated jet by tilting the complete engine; 3) control of angular motion in hover and during transition by direct modulation of engine thrust, even when the engines are operating in afterburning; and 4) using the principle of negative control (i.e., after reaching maximum thrust on one side moments are generated no longer as a pure couple but by further reduction of thrust on the other side only, thereby decreasing over-all thrust level) for the generation of the very large control moments in order to avoid the installation of thrust margins higher than necessary for linear acceleration.

2.2 Flight Vehicles

In the course of the development program three vehicles were built and flight-tested, each being a logical step in the over-all program.

2.2.1. *The hover rig*

The hover rig had three RB 108 engines in a triangular arrangement that was geometrically identical to that of the airplanes in hover configuration, providing similar values of thrust margin and angular acceleration as for the airplanes. The vehicle, which had a VTO-design weight of 2300 kg and was capable to hover for eight min, had a hover autopilot basically identical with that of the airplanes with provisions to operate in either the rate-demand or the attitude-demand mode. It was used for proving the feasibility of thrust modulation for control, test, and optimization of the hover autopilot, for study of hot-gas reingestion and pilot training.

2.2.2. *The VJ 101 C X1*

This experimental airplane had a VTO-design weight of 6080 kg and was fitted with six RB 145 engines without afterburner. Two engines each were mounted in the tiltable wing-tip pods and two in the front part of the fuselage. This vehicle served to prove the capability to hover, to make transitions and fly conventionally at high speeds with special emphasis on low-speed flight. The airplane was used for the development of vertical takeoff and landing techniques, the study of hot-gas-ingestion problems and transition-flight behavior.

2.2.3. *The VJ 101 C X2*

The X2 airplane, with minor differences geometrically identical with the X1, had RB 145 engines with afterburners as lift-cruise engines in the pods. The VTO-design weight was 7900 kg. This vehicle used thrust modulation of engines operating in reheat for hover control. It is capable of flying at supersonic speeds.

2.2.4. *Differences among the vehicles*

The essential difference was weight: $G_{HR}:G_{X1}:G_{X2} = 1:2.64:3.44$. Furthermore, the aerodynamic shape of the hover-rig differed from that of the airplanes.

2.3. Control System

The hover-control system is basically the same for all three vehicles. Control of pitch and roll motions results from thrust modulation of the lift and lift-cruise engines. Yaw control is achieved by differential tilt of the engine pods.

The primary control system is mechanical, linking the stick directly to the fuel control units (FCU's) of the engines and the rudder pedal to the servo-valve of the pod-tilt actuator. The hover autopilot output is fed via hydraulic actuators into the primary control system. Besides motion feedback, the autopilot also obtains a modified pilot input signal stemming from potentiometers measuring stick and pedal deflection.

On the hover-rig this system could be operated in either the attitude-demand or the rate-demand mode for pitch and roll and in the rate-demand mode for yaw. On the X1 and X2 airplanes during hover, the system was operating in the attitude-demand mode for pitch and roll and rate-demand in yaw. During transition, in pitch and roll attitude feedback was reduced as a function of pod-tilt angle, resulting in a gradual change to rate-demand behavior. Decoupling of roll and yaw signals during transition as well as reduction of thrust-control authority was done mechanically as a function of pod-tilt angle. Altitude control, which is acceleration type, is achieved by a conventional gas lever, changing FCU position mechanically.

3. Choice of Data and Procedure of Analysis

3.1. Description of Flight-Test Data

Flight-testing of all vehicles was done under VFR conditions with winds of less than 15 knots average velocity. In order to minimize recirculation problems, the VJ 101 X2 was using a platform with jet deflectors for takeoff and rolling vertical landing with approximately 20 knots of forward speed at impact instead of true vertical landing. The other two vehicles took off and landed from a platform of reinforced concrete without any difficulty.

The fact that in a large number of flights it was left to the pilot to decide the type and sequence of maneuvers flown made it difficult to decide what portions of flight ought to be analyzed in order to obtain results that are representative for maneuvering under specified operational conditions. Therefore only a very limited number of maneuvers was chosen, restricting the analysis to maneuvers that are either necessary for flying at all, such as takeoff and landing, or that might be considered as representative elements of operational maneuvering.

Based on the experience gained during the course of this analysis, coming hover flight tests of the X2 airplane will proceed more systematically. On the other hand, the way the tests were run had the advantage that the pilot was free to develop the type of control technique for maneuvering that he felt to be optimum for himself, representing the best compromise between the requirement of the maneuver and the limited capabilities of the vehicle.

As the VJ 101 had high control powers and a rather low level of configuration-dependent aerodynamic and jet interference when hovering out of ground effects, the only limitation in this respect was the existence of limit-cycle motions due to backlash and elasticity in the control system, requiring a gain reduction in the hover autopilot in order to keep the resulting motions within acceptable limits. Notwithstanding these limitations we feel that the adopted pilot technique and the control-power usage resulting thereof are dominantly influenced by maneuver requirements and that the flight maneuvers chosen for analysis are a representative cross section of maneuvers necessary for hover operations. This holds especially for data taken from hover-rig tests where a number of pilots had the chance to get familiar with this vehicle in a great number of flights.

3.2. Processing of Data

In order to characterize control-power usage and pilot workload, amplitude-density functions and power spectra of control-power usage and pilot's inputs were evaluated for the various maneuvers. Furthermore, correlation of pilot's stick inputs, and of angular acceleration in pitch and roll axes was analyzed. The data used for analysis were available either in analog form, as traces stored on photosensitive paper rolls or on magnetic tape, or in digitalized form as output of high-frequency commutator channels, also on magnetic tape. Stick and pedal inputs of the pilot were recorded directly, whereas control-power usage was computed indirectly in the following way. The output signals of the different channels of the hover autopilot were added to the respective stick and pedal inputs of the pilot with due consideration of the geometrical relations in the control system. The added signal, which corresponds for roll and pitch axes to a change in FCU angle of the engines, was fed into a dynamic model of the engine representing the thrust response due to FCU-angle changes. The resulting thrust response was converted into angular acceleration under consideration of thrust geometry and mass moment of inertia. The dynamic model of the engines was simplified but based on measured responses of the actual engines. The mass moments of inertia were computed, using actual weights of different parts and a weighing of the complete airplane for different loading conditions. Compared with actual flight-test data, calculated frequencies of characteristic motions in aerodynamic flight, using the same source of data for moments of inertia, gave good agreement.

For the evaluation of the amplitude-density functions an analog computer was used. The density functions were evaluated in discrete form, subdividing the full range of acceleration or control displacement into 14 equal sections.

For the determination of power spectra, a Honeywell 9030 frequency analyzer was used. In order to widen the frequency range of the equipment towards lower frequencies, a frequency transformation of the input data was used. The time duration of the samples analyzed differed with type of task from 12 sec (for takeoffs and landings) up to 30 sec (for stabilization).

4. Maneuvers Selected for Analysis

4.1. Problems Concerning the Selection

Control-power usage in hover is influenced by two basic sources. One is effects that depend solely on the maneuver; the other is effects that depend on the configuration. Many effects of the latter group also depend on wind conditions, such as jet interference and recirculation. In actual flight almost all maneuvers represent a mixture of both effects and it is very difficult to either separate these influences for actual maneuvers or design maneuvers that allow a separation.

4.2. Maneuvers Analyzed

The following set of maneuvers was chosen for analysis.

1) Stabilization: holding attitude and altitude constant when flying out of ground effect; with attitude control, this corresponds to flying hands-off after trimming.

2) Displacement maneuvers: longitudinal or lateral displacements, change of heading. All of these maneuvers, representing elements of operational flight, are executed out of ground effect.

3) Vertical takeoff and landing (including rolling vertical landing): take off, climb to a specified altitude out of ground effect, stabilize there; vertical landing on a point specified on ground with or without a limitation on heading angle.

For stabilization, the control-power usage is configuration-dependent. When flying out of ground effect, direct (gust-response) and indirect influence of wind (jet interference and recirculation) together with imperfections of the control-system (backlash, friction, and elasticity) will be the main sources for a type of control-power usage that might be interpreted as "dynamic trim"; i.e., trim of the vehicle with respect to a certain dynamic disturbance level.

For displacement maneuvers as well as for heading changes, control-power usage mainly depends on the type of maneuver, with a possible influence stemming from control-system imperfections. The main difficulty is the proper definition of distances, angle changes, and duration of these maneuvers so that they be representative for operational flight.

Vertical takeoff and vertical landing are rather well-defined elements of operational flying but they also show configuration dependent influences. The weighting factors for these two aspects depend to a high degree on the piloting technique used.

5. Problem Areas for Investigation

5.1. Problem Areas Investigated

The results of the analysis of the maneuvers for the various vehicles may be used to study the following problems:

1) Comparison of control-power usage in the different axes in terms of mean values and maximum values for various maneuvers flown with the same vehicle, in order to check if this relation among maneuvers is about the same for all vehicles. If this is true, flight tests with a hover-rig will generate results that are directly applicable to a similar airplane.

2) Comparison of the variation of mean value and maximum value of control-power usage in each axis for the same maneuver flown with different vehicles, in order to look for a possible influence of vehicle weight.

3) Comparison of control-power usage for various maneuvers flown with the hover-rig in either attitude- or rate-mode control, in order to evaluate the influence of mode of control on control-power usage for various tasks.

4) Determination of the maneuver that requires (under the conditions tested) the highest values of linear mean and maximum value of control power in the different axes of control.

5) Comparison of the amplitude-density function of control-power usage for different vehicles executing the same configuration-dependent flight task under about the same weather conditions in order to check the influence of different aerodynamic shapes and use of afterburner engines on control-power usage.

6) Dependence of pilot control inputs with respect to amplitude and frequency distribution on task and mode of control. Differences in control techniques used by different pilots.

7) Correlation of control power and pilot inputs in pitch and roll, in order to investigate the probability of joint usage of high control powers or large joint pilot inputs for different maneuvers. Influence of piloting techniques on use of correlated inputs.

8) The influence of limit cycles in the control and stabilization system on the distribution of control power and on piloting technique.

5.2. Problem Areas Not Investigated

For hover the following problems were not investigated: 1) the influence of gusty winds and of flight under instrument flight rules (IFR) conditions on control-power usage; and 2) static trim requirements and the influence of wind and ground effect on trim.

Another big area that remained uninvestigated was control-power usage during transition, which indeed is very important. Analysis of this flight condition, where on the VJ 101 control is achieved by both thrust and aerodynamic means, necessitates consideration of both effects at the same time. Analysis of control-power usage for thrust control alone is of no use because the weighting of control by thrust vs control by aerodynamic means is strictly dependent on the type of configuration. At this time simultaneous consideration of both effects was not possible due to limitations in computing equipment.

6. Results and Discussion of Results

6.1. General Remarks

For the hover-rig all maneuvers specified in Sec. 4.2. were analyzed for both rate and attitude modes in pitch and roll and for rate in yaw. Amplitude-density functions and power spectra of control-power usage and of pilot inputs were evaluated for all cases. In order to check the scatter of results, normally up to five different maneuvers of each type were analyzed for each mode of control. For the amplitude-density functions, the averaged distribution was used as being representative, whereas for the power spectra single cases are presented. In this paper no amplitude-density functions are presented. The reader interested in this type of information is referred to Ref. 1.

For both aircraft, only flights with attitude-mode control for pitch and roll were available. For the X1 aircraft the same maneuvers as for the hover-rig were analyzed, whereas for the X2 airplane only takeoff, landing, and stabilization all with and without use of afterburners were investigated.

In further discussion of results, in some cases the linear weighted mean value of the discrete amplitude-density function will be used for characterization of the amplitude-density function. A comparison of scatter of the linear mean values for single tasks with the average value has shown that the percentage of scatter was low. This is astonishing, when one considers that data were taken from flights where the pilot had no specific order of how to fly.

6.2. Control-Power Usage

6.2.1. Comparison of rate and attitude modes of control

Table 1 shows the averaged linear mean values of control-power usage for all tasks analyzed for the hover-rig. From these results it can be concluded that attitude-mode control—

Table 1 Average linear mean values of control-power usage for different tasks [rad/sec²]—vehicle: hover-rig

Axis	Mode	Stabilization	Pitch task	Roll task	Vert. takeoff	Vert. landing
Roll	Attitude	0.091	0.099	0.159	0.160	0.166
	Rate	0.077	0.150	0.215	0.171	0.171
Pitch	Attitude	0.042	0.065	0.049	0.061	0.056
	Rate	0.036	0.062	0.052	0.070	0.065
			Yaw task			
Yaw	Rate	0.013	0.058		0.061[a]	0.035

[a] Initially out of trim.

Table 2 Average linear mean values of control-power usage for different tasks [rad/sec²]—vehicle: VJ 101 X 1

Axis	Mode	Stabilization	Pitch task	Roll task	Vert. takeoff	Vert. landing
Roll	Attitude	0.053	0.059	0.067	0.054	0.075
Pitch	Attitude	0.047	0.075	0.051	0.063	0.067
			Yaw task			
Yaw	Rate	0.011	0.015		0.013	0.011

with the exception of stabilization—will demand less control power than rate-mode control. This holds for weather conditions covered by the tests, i.e., winds up to 15 knots speed with most of the testing done at equal to or less than 10 knots of wind. In the linear mean values the difference is, for most cases, on the order of 10%, with a maximum value of 30% in favor of attitude for displacement maneuvers.

The lower control-power usage of rate control for stabilization is most probably due to the fact that the pilot, working as an attitude stabilizer, shows a threshold effect and is using lower gains in closing the loop than the automatic attitude system does. Therefore the difference is caused by a degradation in over-all performance in the case of rate control.

6.2.2. Comparison of control-power usage for various maneuvers and different vehicles

A comparison of mean values for different maneuvers flown with the hover-rig shows the same trend for both modes of control. Control-power usage is lowest for stabilization. For displacement tasks the mean value for the axis where the maneuvering is done is about 60% higher for attitude and about 100% higher for rate control, than the corresponding value for stabilization. The axis where no maneuvering is done shows a roughly 20% raise for attitude and a 50% raise for rate control compared to the corresponding values for stabilization. The means for vertical takeoff and landing are of the same magnitude as the values for maneuvering in that axis. For some cases the control-power usage for takeoff and landing is dominant. Remembering the fact that the pilots had considerable experience in flying the hover-rig and therefore tended to maneuver rather actively, it seems appropriate to state that for configurations such as the ones analyzed, providing sufficient control power for takeoff and landing will mean sufficient control power for maneuvering in the weather conditions of the tests.

The corresponding analysis for the X1 aircraft presented in Table 2 stresses this point. The comparison of different maneuvers shows the same trend as for the hover-rig, whereas the absolute numbers are lower. A comparison of the results for the X2 airplane, shown in Table 3, with those of the X1 shows no basic difference in roll and yaw but a higher level of pitch usage for the X2. This difference becomes especially apparent for the case of rolling vertical landing of the X2 with afterburning. There is within the X2 results no consistent trend as to the influence of afterburner use. For takeoff and stabilization there is no clearly discernible influence of afterburner use on control-power usage. In the case of landing, due to the difference in technique, there is an understandable growth in pitch usage for rolling vertical landing with afterburners; whereas the higher values in roll and yaw are caused by indirect effects of afterburner use (recirculation). With the exception of the yaw axis of the hover-rig, where maneuvering requires a higher percentage of stabilization usage than usual, all vehicles show for all axes approximately the same ratios of maneuvering to stabilization usage. The difference in yaw usage for the hover-rig was due to the fact that control sensitivity was four times higher than on the airplanes.

In spite of these side effects, it can be concluded from the results presented in Tables 1–3 that the results from hover-rig analysis show within various maneuvers the same trends as those for the airplanes. This proves the fact, already known from pilots' experience, that a similar hover-rig gives results that are directly applicable to the airplane. Using a hover-rig considerably lighter than the airplane will give results that are conservative when applied directly to the airplane. In light of these results, the question posed in item 1 of Sec. 5.1 can be answered positive.

From just looking at the distribution functions, it is difficult to define properly the maximum value of angular acceleration used. Therefore it was decided to use the value of angular acceleration which is sufficient to cover 99% of usage for a maneuver as the maximum value. In the following text and figures these values carry the index 0.99. The ratios of 0.99-maximum value to linear mean value are generally higher than the one representative for a normal distribution. Obviously, the usage distribution is similar to a normal distribution, but with more usage of the higher control powers.

In order to check if there is an influence of vehicle weight on maximum control power used, in Figs. 1–3 the 0.99-maximum control powers for flying in the attitude mode were plotted vs vehicle weight. The results show for roll and yaw a decrease of control power used with growing vehicle weight, whereas for pitch maximum control power used is about independent of weight. For roll and pitch the highest 0.99-maximum value comes from vertical takeoff and landing, with the first one normally being decisive. In yaw the heading-change maneuver results in absolute maximum usage, with takeoff and landing requiring about 80% of this value.

6.2.3. Correlation of control-power usage in pitch and roll axes

A correlation analysis of joint usage of pitch and roll control power shows that the output contains only a low level of correlated signals. For a first approximation, inputs in pitch and roll can be assumed as statistically independent.

Figure 4, presenting a plot of joint roll-pitch usage for eight takeoff and landing maneuvers of the hover-rig flown in attitude-mode control, confirms these results. An ellipse using the 0.99-maximum values for pitch and roll as main axes contains 97% of all control-power usage. The same result holds for the rate-mode case. Applying this to the design of new

Table 3 Average linear mean values of control-power usage for different tasks [rad/sec²]—vehicle: VJ 101 X 2

Axis	Mode	Stabilization with and without afterburner	Vertical takeoff without afterburner	Vertical takeoff with afterburner	Vert. landing without afterburner	Rolling vert. with afterburner
Roll	Attitude	0.062	0.052	0.069	0.069	0.088
Pitch	Attitude	0.057	0.087	0.080	0.077	0.120
Yaw	Rate	0.0063	0.009	0.009	0.011	0.029

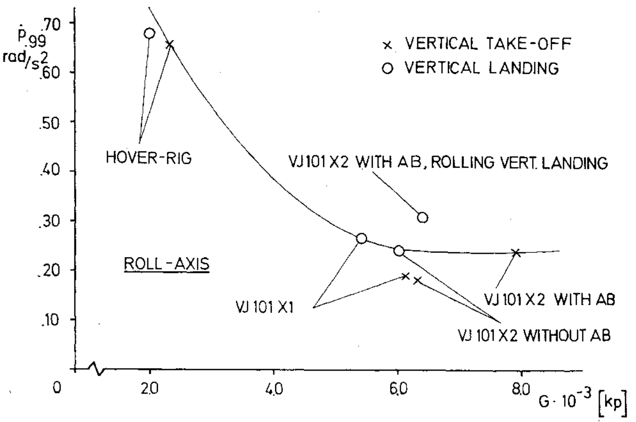

Fig. 1 Maximum values of control power used, covering 99% of total usage (roll axis).

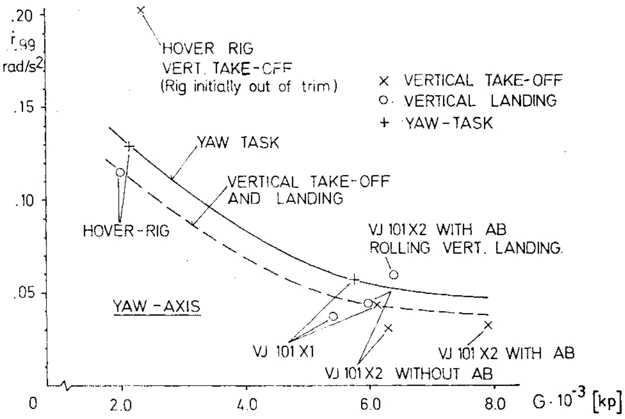

Fig. 3 Maximum values of control power used, covering 99% of total usage (yaw axis).

systems, this means that provided the maximum values for pitch and roll control power are given, the actual design case will be that point along the elliptic contour that is most critical with respect to joint usage. This point normally will depend on the type of configuration considered.

6.3 Pilot Work Load

6.3.1. Comparison of rate and attitude control

The linear mean values of stick and pedal deflection for takeoff and landing of the hover-rig flown in rate- and attitude-mode control are presented in Table 4. A comparison for both modes in pitch and roll shows that the mean values are of the same size. This result does not reflect the difference in pilot rating for both modes. Here, rate mode was always given a lower rating, and with an increased level of external disturbances the rating for rate decreased much faster than it did for attitude. Obviously, the linear mean value is not fit as a sole measure of pilot's concentration in executing a flight maneuver.

Table 4 Average linear mean values of stick/pedal deflection for different tasks [mm]—vehicle: hover-rig

Axis	Mode		Vert. takeoff	Vert. landing
Roll	Rate	$\bar{\delta}_R$	20.6	14.9
	Attitude	$\bar{\delta}_R$	19.3	17.7
Pitch	Rate	$\bar{\delta}_P$	14.0	22.8
	Attitude	$\bar{\delta}_P$	11.6	10.3
Yaw	Rate	$\bar{\delta}_Y$	10.3[a]	2.6

[a] Initially out of trim.

6.3.2. Comparison of pilot inputs for different maneuvers and different vehicles

For comparison, takeoff and landing tasks were chosen. These maneuvers are relatively well-defined and are therefore best fit for this use. The results are presented in Table 5 for the X1 and in Table 6 for the X2 airplane. It becomes obvious the pilots used smaller and smaller inputs in flying hover-rig, X1, and X2, respectively. The X2 results do not show a distinct influence of afterburner use on pilot inputs. From the data available there is no obvious difference in piloting techniques for the three vehicles considered.

Table 5 Average linear mean values of stick/pedal deflection for different tasks [mm]—vehicle: VJ 101 X 1

Axis	Mode		Vert. takeoff	Vert. landing
Roll	Attitude	$\bar{\delta}_R$	8.3	9.7
Pitch	Attitude	$\bar{\delta}_P$	12.5	10.6
Yaw	Rate	$\bar{\delta}_Y$	3.5	2.1

6.3.3. Correlation of stick inputs

Similar to the correlation analysis of joint control-power usage, a correlation study of stick inputs was done. The results are similar to those of the control-power case, showing again only a very low level of correlation. Furthermore, the analysis brought an interesting side result in that the pilot obviously disliked using joint inputs of the nose-down, right-wing-down type. In cases where inputs of this type were necessary, he split up his input into two single-axis inputs. Pre-

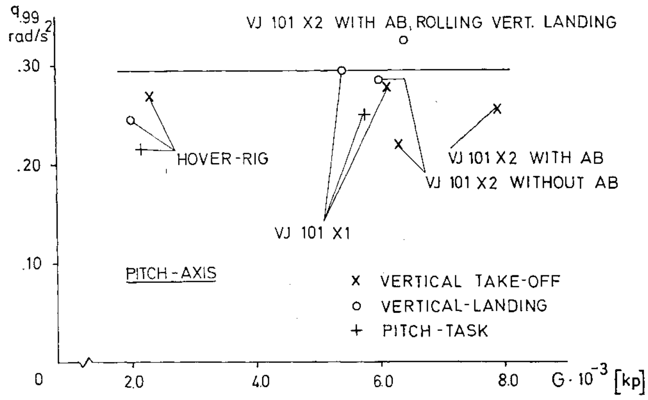

Fig. 2 Maximum values of control power used, covering 99% of total usage (pitch axis).

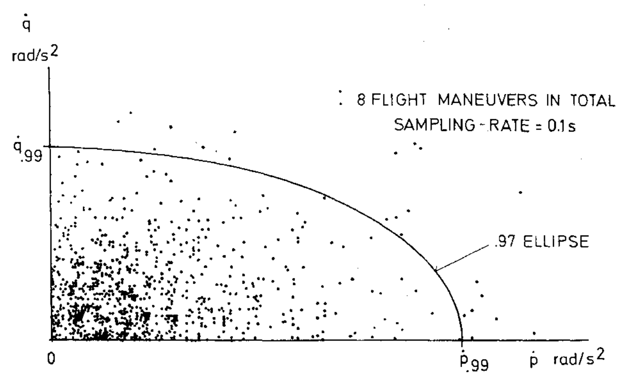

Fig. 4 Joint control-power usage in pitch and roll. Vehicle: hover-rig; mode: attitude; task: vertical takeoff/vertical landing.

Table 6 Average linear mean values of stick/pedal deflection for different tasks[mm]—vehicle: VJ 101 X 2

Axis	Mode		Vert. takeoff without afterburner	Vert. takeoff with afterburner	Vert. landing without afterburner	Rolling vert. landing with afterburner
Roll	Attitude	$\bar{\delta}_R$,	5.5	4.4	4.2	4.0
Pitch	Attitude	$\bar{\delta}_P$,	6.7	5.7	10.2	10.8
Yaw	Rate	$\bar{\delta}_Y$,	4.7	3.8	4.7	7.2

sumably this behavior was due to the relative positioning of the control stick and the pilot's right arm.

6.4. Supplementary Information from Power Spectra

Power spectra of control-power usage of the hover-rig for vertical landing are presented in Figs. 5–7. The plots are for different pilots and different modes of control. The power spectra do not indicate differences due to either mode of control or piloting technique. The inputs of pilot and autopilot are of low-frequency contents with most of the inputs occuring below 0.5 cps. There is no recognizable energy consumption caused by limit cycles in the control system.

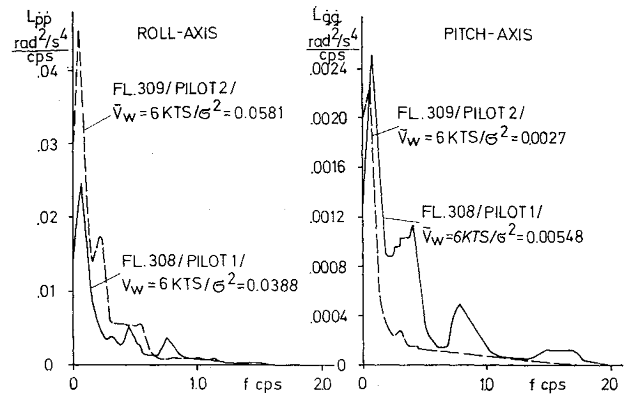

Fig. 5 Power spectrum of angular acceleration usage. Vehicle: hover-rig; task: vertical landing; mode: attitude.

For a comparison, spectra of control-power usage for vertical landings and rolling vertical landings of the X2 airplane are presented in Figs. 8–10. Similar to the hover-rig results, most inputs are again below 0.5 cps, but there is at 1.4 cps in pitch and at 0.5–0.8 cps in roll, a well-defined peak in the spectra caused by limit-cycle motions in the control system. These frequency bands contain a considerable amount of energy which varies for the same maneuver. It is highly probable that the amount of energy depends on pilot technique and test conditions. The results obtained up to now do not allow one to decide if the energy at the limit cycle can be interpreted as excess energy without any actual use. Also it is not yet possible to assess the influence of the limit cycle on the linear mean value and on the 0.99-maximum value of control-power usage in pitch and roll.

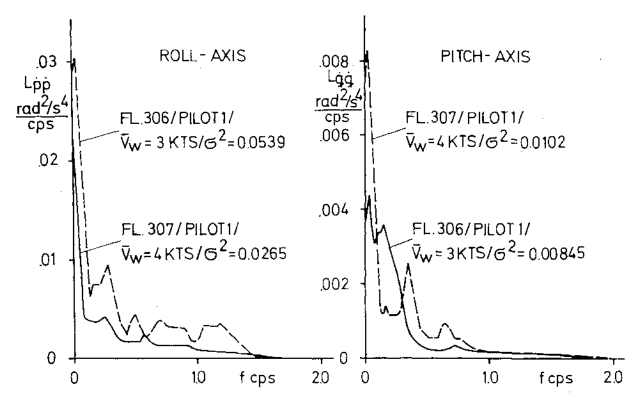

Fig. 6 Power spectrum of angular acceleration usage. Vehicle: hover-righ; task: vertical landing; mode: rate.

7. Comparison of VJ 101 Results with Applicable Recommendations

Figure 11, which was adapted from Ref. 2, shows the 0.99-maximum control-power values of the VJ 101 analysis compared with several recommendations. Also included in this figure are flight-test results of control-power usage from a NASA lunar-landing study[3] that used the X-14 VTOL vehicle. The VJ 101 results and the results from Ref. 3 are in good agreement, and both are considerably below minimum values specified in recommendations. Obviously, both results are representative for relatively calm wind conditions.

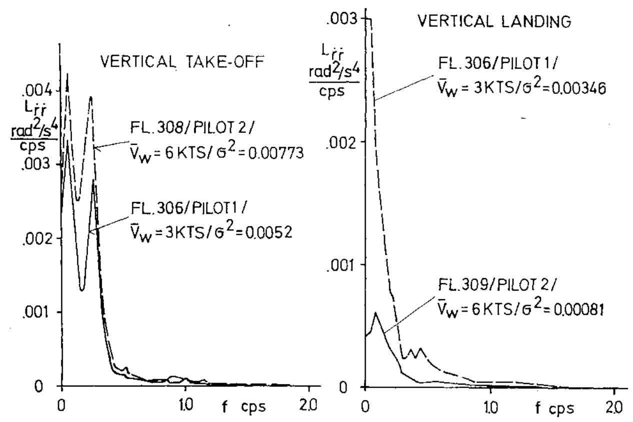

Fig. 7 Power spectrum of angular acceleration usage. Vehicle: hover-rig; mode: rate, yaw axis.

But just this point raises one big question: What are the minimum values specified in recommendations good for? Are they taking care of maneuvering usage? If this is their intention, they seem too high! If they should include the influence

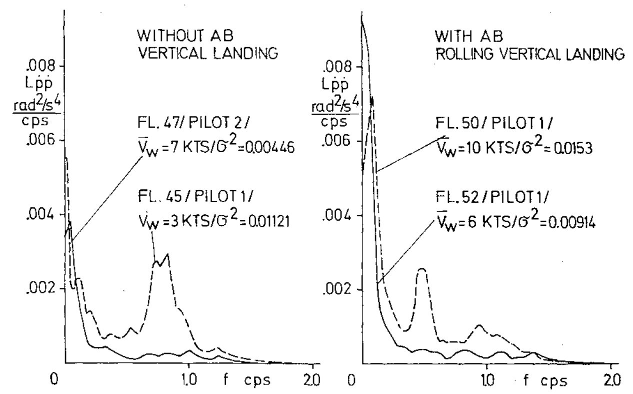

Fig. 8 Power spectrum of angular acceleration usage. Vehicle: VJ 101 X2; task: vertical landing/rolling vertical landing; mode: attitude, roll axis.

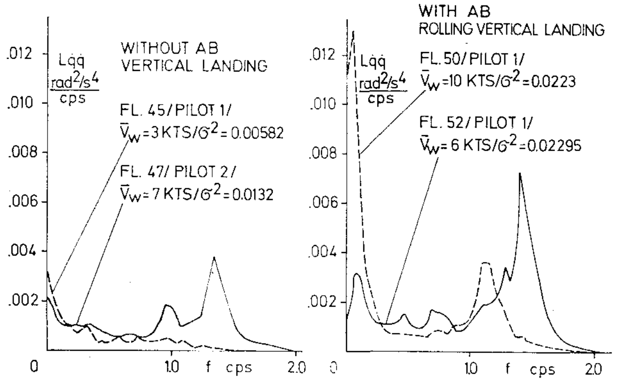

Fig. 9 Power spectrum of angular-acceleration usage. Vehicle: VJ 101 X2; task: vertical landing/rolling vertical landing; mode: attitude/pitch axis.

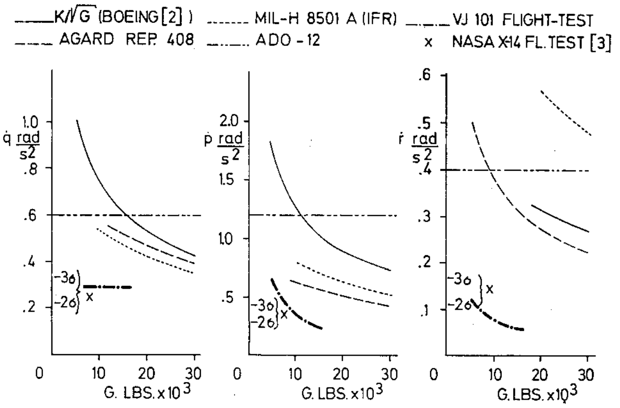

Fig. 11 Comparison of VJ 101; results with recommendations.

of operation under adverse weather conditions (which is a configuration-dependent effect), they are doubtful because there is no information on the type of configuration this influence is representative for. From this it is obvious that a redefinition of the meaning of the recommendations is necessary, taking into account configuration-dependent and maneuver-dependent effects individually in order to improve the reliability of the specifications.

From the results presented it seems doubtful to use vehicle weight as a sole scaling factor for the representation of vehicle size. Furthermore, it is not yet clear if vehicle size alone influences maximum control power.

Also, the joint-usage maneuver specifying joint use of 50% of the maximum control power in all axes simultaneously, as used for example in AGARD Rept. 408, is not stringent enough in the light of the results of this paper. Furthermore, this type of definition does not account for the specific situation of a chosen configuration and therefore might produce results either excessive or insufficient depending on the configuration. Once again we believe that the formulation has to take account of the various possibilities, maybe by using the equal-usage-ellipse concept discussed in Sec. 6.2.3.

8. Summary

The results presented in this paper are in a strict sense valid only for VJ 101-type vehicles, but there are many aspects of general value. From the flight-test data, the following conclusions can be drawn for flight situations in winds up to 15 knots:

Hover-rigs provide data that are directly applicable to the airplane. If the airplane is heavier, which will be the normal case, hover-rig results tend to be conservative.

There is an influence of vehicle weight for roll and yaw axes; for the pitch axis there is none. Attitude-mode control requires, under the conditions tested, 10–30% less control power. The advantage will increase with stronger winds. For this type of vehicle the control-power usage during takeoff and landing is higher or at least as high as in maneuvering. From the data analyzed, no final conclusion can be made as to the numerical influence of aerodynamic shape and use of afterburner engines on control-power usage. Pilot and autopilot inputs are dominantly below 0.5 cps frequency. The power spectra show no difference with respect to mode of control, but differences in piloting technique. Correlation of control-power usage is such that motions in each axis are about statistically independent. Lines of equal joint-usage probability are best approximated by ellipses. Limit-cycle motions have an influence on control-power usage. The dependency on various factors is not yet understood. This also holds for the interpretation of the extra energy generated. The comparison of maximum control powers with NASA data shows good agreement. The values experienced are much lower as those required by recommendations.

Therefore, the results of this analysis stress the need for a revision of current specifications and recommendations, taking into account not only the experience with one type of configuration but experience gained with as many vehicles as possible in order to cover the broadest scope possible.

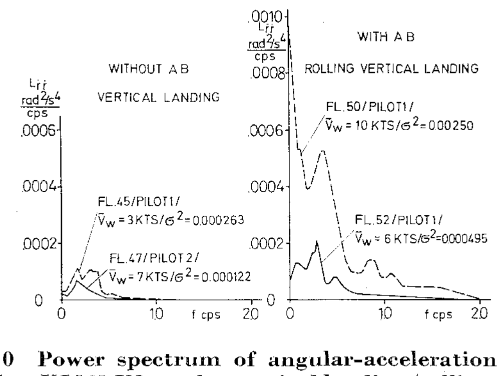

Fig. 10 Power spectrum of angular-acceleration usage. Vehicle: VJ 101 X2; task: vertical landing/rolling vertical landing; mode: rate, yaw axis.

References

[1] Schaeffler, J., Alscher, H., Steinmetz, G., and Sinacori, J. B., "Control-power usage for typical flight maneuvering in hover from a systematic analysis of flight test data of the VJ 101 aircraft and of a hover-rig," AIAA Paper 66–816 (1966).

[2] "VTOL—operating considerations," The Boeing Company Rept. D6-8678 (July 1964).

[3] Rolls, S. L. and Drinkwater, F. J., III, "A flight evaluation of lunar landing trajectories using a VTOL test vehicle," NASA TN D-1649 (February 1963).