New Longitudinal Handling Qualities Data—Carrier Approach

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The results of an aircraft flying qualities research program sponsored by the Naval Air Systems Command are presented. Navy test pilot evaluations in the form of pilot ratings and specific comments of several longitudinal handling characteristics were obtained for a simulated carrier landing task. The investigation made use of a variable stability aircraft which accurately simulated the longitudinal short-period response characteristics and the effects of atmospheric turbulence. The flying qualities associated with variations in short-period frequency (ω_{sp} range of 0.6–2.0), lift curve slope (L_α/V range of 0.6–1.35), and the use of direct lift control are presented. The data are compared with similar data obtained from flight and ground simulator tests. All configurations tested were found to be acceptable for the daylight visual carrier approach task, and only minor differences in the flying qualities of the configurations were evident.

Nomenclature

DLC = direct lift control
F_s/g = stick force/g, lb/g
IAS = indicated airspeed, fps
L_α/V = lift curve slope/velocity, 1/sec
M_α = angle of attack stability, 1/sec²
$M_{\dot\alpha}$ = angle of attack damping, 1/sec
$M_{\delta e}$ = longitudinal control stick sensitivity, rad/sec²/in.
$M_{\dot\theta}$ = pitch damping, 1/sec
V = velocity, fps
g = acceleration due to gravity, 32.2 fps²
n_{z_α} = normal acceleration response to α, g/rad
α = angle of attack, rad
ζ_{sp} = longitudinal short-period damping ratio
ω_{sp} = undamped longitudinal short-period frequency, rad/sec

I. Introduction

In the fall of 1968, a flight test program was initiated by Princeton University under sponsorship of the Naval Air Systems Command for the purpose of determining the influence of longitudinal short-period frequency and normal acceleration response on flying qualities for the carrier landing approach. The tests were conducted by making simulated carrier landing approaches with a variable stability airplane in a simulated atmospheric turbulence environment, duplicating the flight task used in past investigations by Princeton University.[1–5] Recent improvements to the variable stability system pitching moment and heave controls permitted an extension of the range of variables previously investigated with the variable stability airplane.[2] The results of the tests and a comparison with other investigations are discussed herein. Additionally, pilots' impressions of a separate lift controller (DLC) are presented.

II. Experimental Procedure

A. Variable Stability Airplane

The Princeton variable stability Navion airplane shown in Fig. 1 was used to obtain the stability configurations investigated in this program. The airplane's variable stability control system consists of a four-axis autopilot and servo system which provides aileron, rudder, elevator, and flap deflections proportional to sensed angular rates, angle of sideslip, and angle of attack. The basic aerodynamic moment and lift characteristics of the airplane are thereby altered to achieve a wide range of stability and control configurations. Side force and drag characteristics are those of the basic airplane and were not varied in these tests. A fixed lateral-directional simulation of a typical carrier aircraft was used with all configurations. Random noise signals stored in an onboard tape recorder were filtered and summed with other inputs to the controls to provide calibrated simulated turbulence. In the longitudinal mode these signals produced both correlated and uncorrelated pitch and heave disturbances.

The right seat controls and flight instruments for the evaluation pilot were configured similar to those of a typical Navy jet fighter. Stick force gradients were generally consistent with the artificial feel systems of contemporary jet fighters and were 4.0 lb/in. longitudinally and 4.5 lb/in. laterally. The rudder pedal gradient was 25 lb/in. A standard T arrangement of primary flight instruments was used. The left seat was occupied by a safety pilot who performed the tasks of monitoring over-all system performance for safe operation and setting up the various test configurations.

B. Flight Problem

The basic evaluation task of this study was a simulated power approach to a carrier landing under moderately turbulent conditions. The simulated approaches were made to the Princeton runway, whose width of 70 ft corresponds to the painted area on a carrier deck. Glide slope information was provided by an optical landing aid, developed for Marine Corps advanced airfield use, which was installed at the side of the runway. An approach speed of 105 knots was used to match the closure speed of a jet flying at 135 knots IAS, approaching a carrier with 30 knots of wind over the deck.

The procedure for conducting a test run is illustrated in Fig. 2. All runs were made in smooth air so that the response of the simulated configuration to the calibrated artificial turbulence would not be distorted. An analog matching

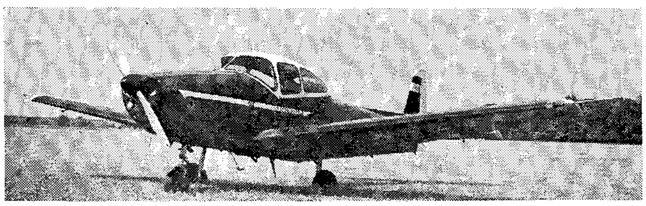

Fig. 1 Variable stability Navion.

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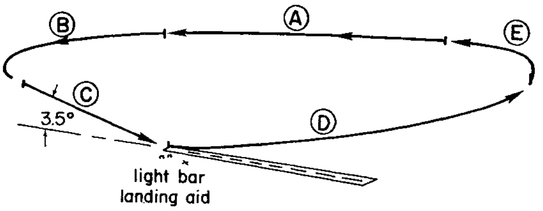

RACETRACK FLIGHT PATTERN PHASES

- (A) Downwind leg, 800' alt. – evaluation pilot takes over and feels out airplane
- (B) 180° turn by evaluation pilot
- (C) Final approach begins approximately one mile out at the discretion of the evaluation pilot. 3.5° glide slope and configuration approach speed maintained by the evaluation pilot.
- (D) Waveoff and climbout – evaluation pilot transmits rating and comments
- (E) Safety pilot re-configures airplane for next approach

Fig. 2 Flight pattern.

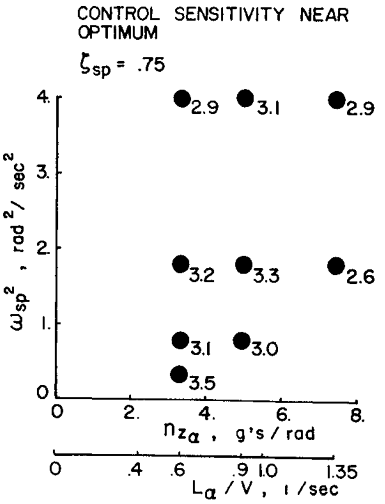

Fig. 3 Pilot ratings of longitudinal short period characteristics.

technique was used to achieve an accurate correspondence between the dynamics and control response of the variable stability airplane and of each test configuration.

C. Evaluation Pilots and Rating System

Five evaluation pilots were provided by the Naval Air Test Center at Patuxent River, Md., and were graduates of the Navy Test Pilot School. They included representatives of the Flying Qualities and Performance, Service Test, and Test Pilot School Branches of the Center. The engineering test pilot at Princeton University also participated in the program.

The revised Cooper-Harper rating system[6] shown in Table 1 was used by the pilots to evaluate the various configurations. The incremental difference in rating between configurations was consistent for all pilots, although some overall bias in the absolute rating number was evident between pilots (some pilots tended to rate all configurations higher or lower than the average pilot). The pilot ratings of this report are the average of the six pilots.

III. Results

A. Configurations and Ratings

A nine configuration matrix of variations in the short-period frequency ω_{sp} and normal acceleration response n_{z_α} was selected for the test program (Table 2). The values of ω_{sp} and n_{z_α} used were all less than those of the basic variable stability aircraft. The minimum value of the parameters was determined by the constraints $M_\alpha \leq 0$, $M_{\dot\alpha} + M_{\dot\theta} \leq 0$, and $\zeta_{sp} = 0.7$ in the case of ω_{sp}, and by the limited flap authority in the case of n_{z_α}. At the lowest n_{z_α} the available angle of attack range for maneuvering was ±2.5° which is

Table 1 Pilot rating scale

Controllable: Capable of being controlled or managed in context of mission, with available pilot attention.	Acceptable: May have deficiencies which warrant improvement but adequate for mission. Pilot compensation, if required to achieve acceptable performance, is feasible.	Satisfactory: Meets all requirements and expectations. Good enough without improvement. Clearly adequate for mission.	Excellent, highly desirable.	A1
			Good, pleasant, well behaved.	A2
			Fair, some mildly unpleasant characteristics. Good enough for mission without improvement.	A3
		Unsatisfactory: Reluctantly acceptable deficiencies which warrant improvement. Performance adequate for mission with feasible pilot compensation.	Some minor but annoying deficiencies. Improvement is requested. Effect on performance is easily compensated for by pilot.	A4
			Moderately objectionable deficiencies. Improvement is needed. Reasonable performance requires considerable pilot compensation.	A5
			Very objectionable deficiencies. Major improvements are needed. Requires best available pilot compensation to achieve acceptable performance.	A6
	Unacceptable: Deficiencies which require mandatory improvement. Inadequate performance for mission even with maximum feasible pilot compensation.		Major deficiencies which require mandatory improvement for acceptance. Controllable. Performance inadequate for mission, or pilot compensation required for minimum acceptable performance in mission is too high.	U7
			Controllable with difficulty. Requires substantial pilot skill and attention to retain control and continue mission.	U8
			Marginally controllable in mission. Requires maximum available pilot skill and attention to retain control.	U9
Uncontrollable: Control will be lost during some portion of mission.			Uncontrollable in mission.	10

Table 2 Configuration derivative and parameter values

Configuration	L_α/V	ω_{sp}	ζ_{sp}	$\zeta_{sp}\cdot\omega_{sp}$	$n_{z\alpha}$	$L_\alpha/V/\omega_{sp}$	C.A.P.[a]	M_α	$M_{\dot\theta}$	$M_{\dot\alpha}$	Average pilot rating
14	0.60	0.60	0.75	0.45	3.30	1.00	0.108	−0.80	0.83	−0.91	3.5
16	0.60	0.90	0.75	0.67	3.30	0.66	0.244	−0.92	0.19	−0.91	3.1
20	0.60	1.35	0.75	1.01	3.30	0.44	0.551	−1.51	−0.51	−0.91	3.2
40	0.60	2.00	0.75	1.50	3.30	0.30	1.209	−3.10	−1.49	−0.91	2.9
23	0.90	0.90	0.75	0.67	4.95	1.00	0.163	−1.28	0.58	−0.91	3.0
26	0.90	1.35	0.75	1.01	4.95	0.66	0.367	−1.62	−0.21	−0.91	3.3
48	0.90	2.00	0.75	1.50	4.95	0.45	0.806	−2.92	−1.19	−0.91	3.1
29	1.35	1.35	0.75	1.01	7.43	1.00	0.244	−2.18	0.30	−0.91	2.6
32	1.35	2.00	0.75	1.50	7.43	0.67	0.537	−3.00	−0.74	−0.91	2.9

[a] C.A.P. = $\omega_{sp}^2/n_{z_\alpha}$, C.A.P. = Control Anticipation Parameter.

equivalent to ±0.15 g at this n_{z_α} (angle of attack variations in excess of this limit would bottom the flaps of the variable stability aircraft).

Average Cooper-Harper ratings and the matrix of configurations are shown in Fig. 3. As can be seen, there is very little difference among configurations with respect to the ability of the pilot to perform the carrier landing task. At the good damping ratio of $\zeta_{sp} = 0.75$ of these tests, the difference in pilot rating between the best and poorest configurations was less than one unit. Pilot commentary reflected the slight difference between configurations. Pilots did note a very gradual decline in good handling qualities as either the short-period frequency or normal acceleration response was reduced. (Normal acceleration response n_{z_α} is used in this report; however, lift curve slope L_α/V is equally applicable to all statements. The relative importance of these two parameters, particularly in the limited carrier approach speed regime, remains controversial.) The configuration having the highest short-period frequency ω_{sp} at the lowest n_{z_α} did not present any problem; in fact, was preferable to lower ω_{sp} values. For comparison with the configurations tested, it might be noted that typical carrier aircraft have a normal acceleration response of $n_{z_\alpha} \approx 3$ and a short-period frequency of $\omega_{sp} \approx 1$ ($\omega_{sp}^2 \approx 1$).

B. Control Sensitivity

Pilots were allowed to select a desirable control sensitivity for each configuration. To expedite the tests, a control sensitivity determined during initial shakedown flights was used as a starting point. In most cases the pilots commented that the sensitivity was near optimum although some pilots did readjust the sensitivity to a slightly higher or lower value. No variation in pilot-selected control sensitivity at a given short-period frequency was evident as the normal acceleration response was varied. The pilots' average control sensitivity as a function of the squared short-period frequency is shown in Fig. 4.

C. Data Comparison

A comparison of the data previously discussed in Fig. 3 with that obtained in similar studies is shown in Fig. 5. Cooper-Harper ratings and stick force/g are listed fo reach configuration, above and below the symbol, respectively. The data of Eney[2] and Mooij[4] were both obtained at Princeton using the same variable stability aircraft, Navy carrier qualified pilots, and task as the data of this report (Miller).

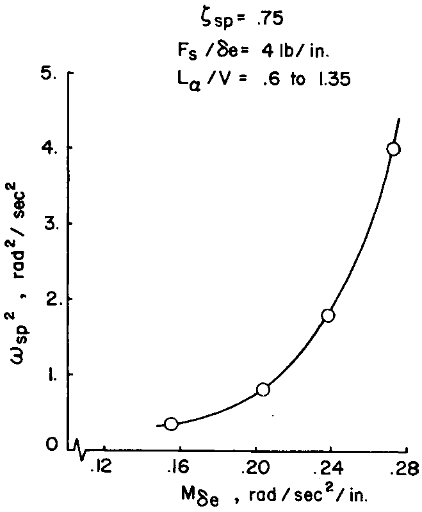

Fig. 4 Pilot selected control sensitivity.

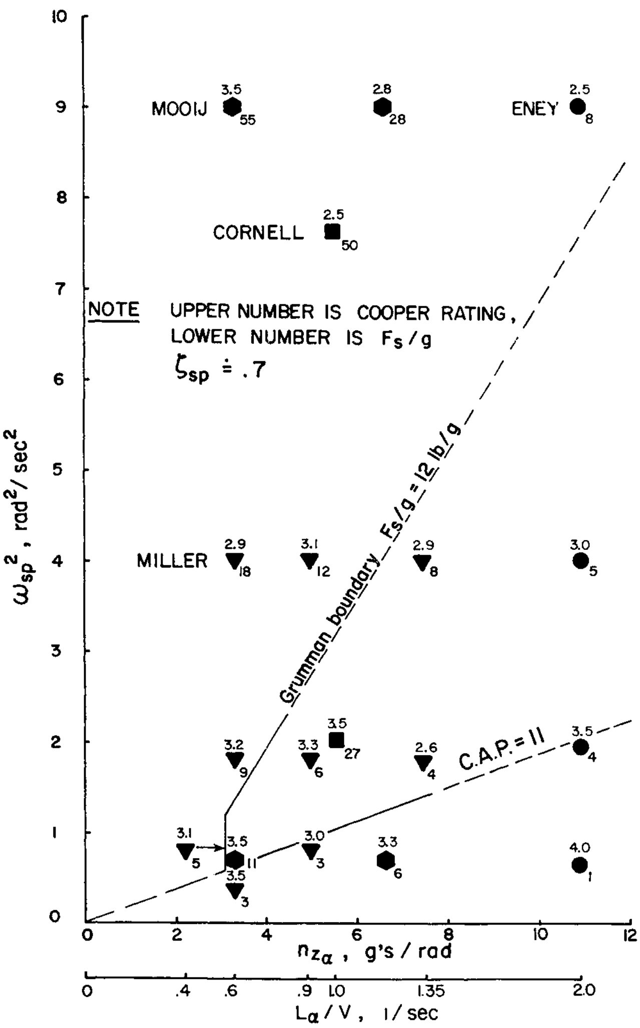

Fig. 5 Pilot rating and stick force/g data comparison.

The data of Cornell[7] are also flight data, obtained with a variable stability T-33 on a landing approach task (the Cornell[7] data for operation on the front side of the power required curve are shown). It is evident that the recent data of this report are consistent with previous flight studies. There is disagreement with some recent results obtained with a moving base simulator (Grumman boundary).[8] Although the lower ω_{sp} and minimum n_{z_α} boundaries appear reasonable based on flight data, there is a large discrepancy regarding high short-period frequency at low values of n_{z_α}. As noted previously, increases in short period frequency ω_{sp} were always beneficial (or at least, not degrading) in the flight program. The data of Mooij[4] and Cornell[7] confirm the trend noted in this reported test program.

A possible explanation for the restrictive upper Grumman boundary[8] is that the Grumman tests were conducted at a fixed level of stick force/g of $F_s/g = 12$ lb/g (pilots were not allowed to optimize the stick sensitivity). This could result in an overly sensitive control response (high $M_{\delta e}$, rad/sec^2/in.) at the higher short-period frequencies. For example, if Mooij's configuration rated 3.5 with $F_s/g = 55$ lb/g (upper left-hand corner of Fig. 5) were flown with the stick force/g of the Grumman tests, it would have over four times the control sensitivity $M_{\delta e}$ ($55 \div 12$). The pilot comments of the Grumman tests,[8] "pitch sensitive, nose bobbing," could be interpreted as a control sensitivity rather than excessive short-period frequency problem. Considering the large range of stick force/g of the configurations shown in Fig. 5, and the relatively minor variation in pilot opinion, it seems evident that stick force g is not an important parameter to the pilot on approach.

The data appear to confirm the lower boundary of Ref. 8. This boundary is a level of the Control Anticipation Parameter CAP[9] of $11°$/sec^2/g (CAP $\approx \omega_n^2/n_{z_\alpha}$).

D. Direct Lift Control

After completing the ω_{sp}, n_{z_α} portion of the test program, the pilots were asked to evaluate the use of a direct lift control (this control was also investigated in Ref. 4). A separate thumbwheel controller on the top of the control stick proportionally commanded deflection of the aircraft flaps. Maximum authority was limited to $\pm 0.15\,g$. Although most pilots had never used this type of control before, they all quickly adapted to its use. In general, the pilots were not inclined to change their evaluation or Cooper-Harper rating of a configuration with the addition of DLC (actually, all configurations were satisfactory without its use). They did appreciate the ability to make corrections close to the simulated touchdown which they could not otherwise do with the configuration. Relatively little improvement is realized far out on the glide slope and a few commented that you could get into trouble by concentrating too heavily on this control in the early stages of the approach. One pilot even stated that its use might be undesirable because a *novice* pilot might incorrectly rely too heavily on it and get into trouble on the approach. All were impressed by their adaptability to the control and the ease of making last moment corrections close to touchdown. Final meatball control of even the most responsive (best) configurations was improved with its use.

IV. Conclusions

The following are conclusions for the visual carrier approach task, with operation on the front side of the power required curve, and good short-period damping ratio: 1) Only mild gradients of pilot opinion are evident for the range of variation of short-period frequency and normal acceleration response studied in this report. 2) Contrary to recent ground simulator studies, no difficulty in flying configurations with high short-period frequency and low normal acceleration response was noted. 3) Stick force/g is not an important parameter to the pilot on approach. 4) Use of a separate direct lift (normal acceleration) control, DLC, was beneficial for all configurations for small altitude corrections in the final moments up to (simulated) touchdown.

V. References

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SYNOPTIC: Transonic Buffet Characteristics of 60° Swept Wing with Design Variation,

J. F. Mayes, M. E. Lores, and H. R. Barnard, LTV Aerospace Corporation, Dallas, Texas; *Journal of Aircraft*, Vol. 7, No. 6, pp. 524–530.

Aircraft Configuration Design

Theme

The paper is an analysis and design investigation of wings for fighter aircraft to obtain high-lift buffet-free flight at Mach numbers near 0.9. It presents results of wind-tunnel tests conducted to verify design trends and extrapolations determined from existing data.

Content

The paper contains a brief review of current wind-tunnel and flight test information, with the objective of identifying desirable geometric characteristics of a wing for buffet-free flight at Mach 0.9. Results of this review are as follows: 1) Wing thickness ratio should be as low as structural limitations will permit; 2) Increased wing sweep will permit higher thickness ratios to be used; 3) Camber or leading edge droop can be used provided sufficient wing sweep is also used; 4) For any combination of the aforementioned variables, an optimum aspect ratio may exist; 5) Wing-root design and wing-body fairing is important and higly configuration-dependent. Rapid increase in body cross section near the wing trailing edge contributes to local separation in that region.

In addition to the previously mentioned qualitative trends, specific magnitudes were obtained for the most desirable wing geometry. A wing with a leading edge sweep of 60° and thickness ratio of 0.05 was selected to permit increase of camber from 0.2 to 0.4 without encountering severe shock-induced effects. Simulation of camber, often necessary for practical design, was obtained by a 5° leading edge droop and a 5° trailing edge flap. No attempt was made to optimize this angle. Only basic design trends and magnitudes were desired. As shown in Fig. 1, W_{12} has a constant 0.2 camber and provisions for leading and trailing edge droop. W_{13} has a constant 0.4 camber with mean line *a* equal to 0.5 as does W_{12}. W_{14} in an isobar design. Effects of camber were determined from W_{12} and W_{13}. Leading and trailing edge droop on W_{12} permitted evaluation of these devices in producing increased camber. W_{14} provided information as to the effect of camber variation with span and leading edge tip shape. Inboard and outboard glove designs, representative of full-scale thickness and contour, were fabricated and tested on each wing. Results of wind-tunnel tests at Mach 0.75–0.92 are presented in the paper for three wings having design features formerly identified. Composite data are presented showing: lift coefficient, axial force, trailing edge pressure, and wing-root bending moment (rms) variations with angle of attack. Oil flow photographs are also presented to show the onset of flow separation on the wings.

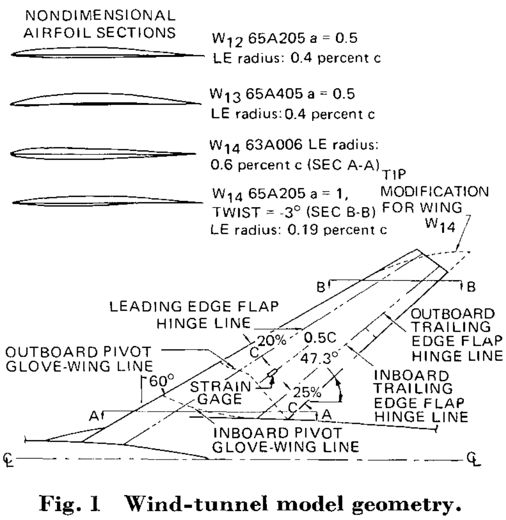

Fig. 1 Wind-tunnel model geometry.

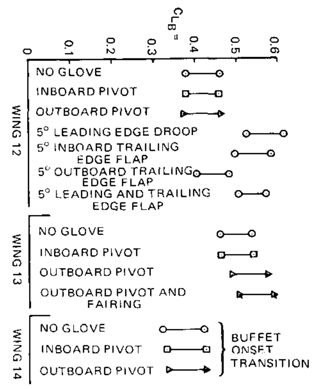

Fig. 2 Summary of buffet wind-tunnel data for wings 12, 13, and 14 at Mach 0.9.

Results of the wind-tunnel tests at Mach 0.9 are summarized in Fig. 2 for transition levels of buffet-onset lift coefficient. The most impressive results obtained for this series of tests are for W_{12} with 5° leading edge droop. Strain gage rms data show a C_{LB} transition between 0.525 and 0.59. The unusually high rms value of 17.5 at C_L of 0.59 and the decreasing trend as angle of attack is increased was not observed for the other configurations. Repeat runs obtained during oil flow tests provided confirmation of the trend. A possible explanation is that some degree of coupling between the structural characteristics of the aluminum wing and aerodynamic load fluctuations occurred for C_L values above 0.525.

The following conclusions are given within the scope of geometry and test conditions of this paper. It is believed that the design trends are applicable to wings with 50°–65° of sweep and airfoil sections with approximately the same streamwise thickness ratio and maximum thickness position. The conclusions are:

1) Wind-tunnel results confirmed the validity of using the Mach number normal to the leading edge to relate the buffet improvement trend for wings with low sweep to that of wings with high sweep for the same streamwise camber.

2) Leading or trailing edge droop provides about the same buffet improvement as increasing camber from 0.2–0.4. Simultaneous use of leading and trailing edge droop does not improve buffet characteristics over that for each device used separately.

3) Use of an airfoil with a mean line definition of $a = 1.0$ increases the upper surface trailing edge slope and produces early separation.

4) Buffet-lift coefficients obtained in the VAD tests are compatible with previous wind-tunnel and flight test results.

5) Presentation of wind-tunnel buffet data in composite form enables the investigator to identify buffet-onset lift coefficient and the region on the wing where separation occurs. In many cases the cause of separation and possible remedies can be more easily determined from the data in this format.