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Identification of the Transfer Function Between Turbulence and Aircraft

Qing Chen* and Gunther Schänzer†
Technical University of Braunschweig, D-3300 Braunschweig, Germany

As the procedure to measure wind in flight is fairly well developed, it becomes possible to identify the transfer function between turbulence and an aircraft. In the view of system theory and the inherent nature of an aircraft, the approach to identification is divided into two steps: first, to estimate steady aerodynamic derivatives by flight in smooth air; second, to identify the higher frequency aerodynamic transfer function by flying in a turbulent atmosphere. The latter is mainly studied here. The airplane is considered as a "two-point" model to describe more physically the dynamic response of an aircraft due to turbulence and the complex interaction among different parts of the airplane. The relevant effects, as far as possible, have been taken into account for simulating the complete aircraft model, which includes a model for the rigid aircraft motion and a model corresponding to the effect of turbulence. The latter unknown model is established on the analysis of its physical background. An example is demonstrated by flight test data of the research aircraft Dornier DO 128 of the Technical University of Braunschweig. This aircraft has an additional time lag of 0.1 s that will include primarily the effects of unsteady aerodynamics.

Nomenclature

a_z = acceleration in z direction
b = wing span
b_i = parameter to identify
C_m = coefficient of pitch moment
C_L = lift coefficient of wing
$\bar{c}$ = wing mean chord
F = thrust
F_0 = identified parameter
f_w = constant
G = gravity
$G(s)$ = transfer function
I_y = moment of inertia about y axis
J = performance index
k_μ = constant
l = distance between neutral points of wing and tail
M = pitch moment
q = pitch rate
R_f = vertical distance between thrust line and center of gravity
r_α, r_{a_z} = weighting factors of α and a_z
S = wing area
T_i^* = time constant
u, w = velocity components in x axis and y axis
V = airspeed, $V = \sqrt{u^2 + w^2}$
V_0 = given identified parameter
X, Z = resultant forces in x and z direction
α = angle of attack
γ = flight-path angle
δ_a = angle of flap
Θ = pitch angle
σ = angle between thrust line and body-fixed axes
τ = nondimensional distance
τ_t = time delay
φ = indicial admittance

Subscripts
a = aerodynamic axes (wind axes) of wing
at = aerodynamic axes of tail
dw = downwash
g = earth-fixed axes
k = flight-path-fixed axes
kg = projection of flight-path-fixed axes on earth-fixed axes
m = measurement
t = tail
w = wing or wind

Introduction

SINCE the beginning of human flight, the aircraft response to turbulence has been a topic of great interest for structural loads, flight-path guidance, passenger comfort, and flight safety as well. From early theoretical research to later wind-tunnel experiments, until recently well-developed measurement technique in flight test, many theoretical investigations and practical experiences have been contributed to this subject. However, even now it is still problematic to describe with sufficient accuracy the dynamical model of the aircraft's motion for flying in turbulence. The reasons lie in the two basic problems: aircraft's modeling and measurement technique.

The principle for system identification with flight test is shown in Fig. 1. Since turbulence in flight was very difficult to measure owing to unsufficient precision of measurement, the identification of aircraft's model is mostly concentrated on the flight test in smooth air with pilot input. The always existing turbulence will be sometimes explained as process noise. On another side, some wind models had to be assumed on the basis of global approximation, as shown by the broken line in Fig. 1. In microaspect, it has been studied by Kolmogorov law,[1] cascade theory,[2] etc; in macroaspect, it has been mosly approximated by Dryden or von Kármán model in application. It was not until the last decade that the measurement of wind in flight became possible.[3,4] Many efforts have been made during these 10 years to improve the measurement accuracy by means of developing capability of onboard computers and quality of sensors as well as measuring techniques. Today with this great advantage the turbulence model is no longer necessary.

In the essential view of the theory of a large system, the modeling of aircraft will become simple if we separate the large system into several small subsystems. As shown in Fig.

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*Guest Researcher, Beijing University of Aeronautics and Astronautics, People's Republic of China.

†Professor, Head of the Institute for Flight Control and Guidance, Department of Mechanics, Hans-Sommer Str. 66.

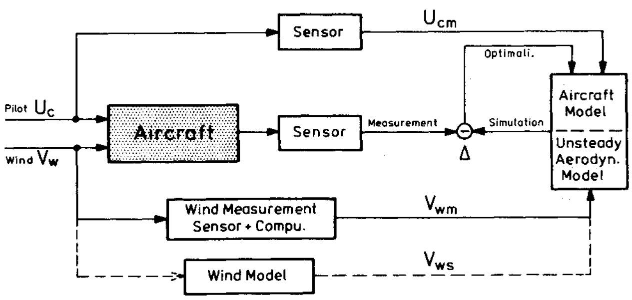

Fig. 1 General block diagram of system identification.

1, the whole system of an actual aircraft is considered as the combination of two subsystems: conventional aircraft model and the transfer function between aircraft and turbulence. The former differs for various concerned problems, such as handling qualities, aeroelasticity, flight control design, and so on. For the problem of the response to turbulence, the turbulence includes many components of various wavelengths. Many researches have indicated that an aircraft can be taken as a "one-point" model in the case of large wavelength turbulence and relatively small size aircraft, and then the assumption of steady or quasisteady aerodynamics is suitable. If the turbulence scale is compared relative to the size of aircraft, a "multipoint" model should be considered or gradient method should be applied for "one-point" model.

Until now, as far as available literatures are concerned, the transfer function between aircraft and turbulence has never been identified with flight test or wind-tunnel experiments. Usually it has only been treated in the following three ways. The first way is to take turbulence as quasisteady external disturbance, which is mathematically equivalent to a steady change of aircraft motion, then aerodynamical derivatives become the transfer function.[5–7] The second way[5,8–10] is based on the previous way and introduces Küssner's or Sears' function that was calculated from two-dimensional thin airfoil theory,[11,12] or using simple lifting line theory for finite aspect ratio.[13] The third way is to treat turbulence generally as process noise.[14] Furthermore, many investigations are based on the assumption of the turbulence model as Dryden or von Kármán spectrum distribution. Problems occurred when using the aforementioned methods. In parameter identification, the same quasisteady aerodynamic model would yield different results when using the data for flying in smooth air or in turbulent atmosphere,[7] which is unreasonable. The Küssner's function[13] may be inaccurate for wings with finite aspect ratios because of using the simple lifting line theory.[15] The results obtained from the Dryden or von Kármán model have a problem of correlation between real actual aircraft response and the assumed wind model. Furthermore, the results of identification depend on the assumed wind model.[16] Finally, the assumption of turbulence as process noise generally does not cover the physical reality of problem. In other words, the assumed aircraft model cannot describe the aircraft motion completely, since the residual, such as the special response to turbulence, is replaced by process noise.

This paper is intended to identify the transfer function between turbulence and an aircraft for the longitudinal motion by means of flight test, wind measurement, physical modeling, numerical simulation, and parameter estimation.

System Modeling

Facing the two basic problems, a new approach is proposed on the basis of the available situation in the presented work, as shown in Fig. 2. The key points lie in the following:

1) The influence of sensor dynamics is eliminated by data compatibility check and off-line correction before identification; thus it is not taken into account in system modeling.

2) The measured wind and measured control signals are taken as direct inputs for simulation.

3) The inherent dynamic characteristics of a made aircraft will not change. They can only be excited out by correspondently external disturbance.

In this way, the motion of aircraft flying in turbulent air can be taken as the superposition of low-frequency rigid eigenmotion and high-frequency response to turbulence, i.e., the combination of two subsystems in Fig. 2.

In light of this strategy, the flight test can also be separated into the response of different inputs; then the measured data are used to identify the relevant subsystem. For current work the flight test was planned as follows:

1) In smooth air (with average wind), maneuvering flight is carried out to excite out the eigenmotions of aircraft, which is used to estimate the steady aerodynamical model and the thrust model.

2) In strong turbulent air the aircraft is first trimmed in a state of steady and horizontal rectilinear flight. By fixing all control and power, the pilot lets the aircraft experience the variation of turbulence. These data are used for estimating the transfer function between aircraft and turbulence.

During the flight the wind components and aircraft's reaction are accurately measured. The assumed model is identified by minimizing the difference between measurement and simulation (see Fig. 2).

In the rest of this section, each block drawn in Fig. 2 will be described in more detail.

Aircraft Model

Based on one of the key points mentioned in the beginning of this section and available results of parameter identification that were made in smooth air,[17,18] the current work focuses on identifying the transfer function between aircraft and turbulence for longitudinal motion. For this purpose the response to turbulence must be separated from the complete dynamic motion of aircraft. In other words, relevant effects involved in the complete motion should be, as far as possible, taken into account in the mathematical modeling and numerical simulating of the aircraft model to eliminate their influence on identifying the unknown transfer function.

The aircraft is considered as "two point" model[19]—wing and tail. The generally nonlinear equations of aircraft longitudinal motion are expressed in the earth-fixed coordinate system, as shown in Fig. 3; namely

$$m\dot{u}_{kg} = X_g + F\cos(\Theta + \sigma) \tag{1}$$

$$m\dot{w}_{kg} = Z_g - F\sin(\Theta + \sigma) + G \tag{2}$$

$$I_y\dot{q} = M + F*R_f \tag{3}$$

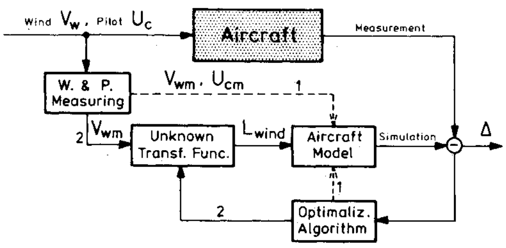

Fig. 2 Block diagram of the presented strategy.

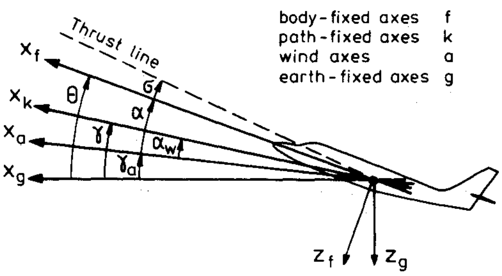

Fig. 3 Definition of angles in different coordinate systems.

The resultant forces X_g and Z_g are contributed by the wing and the tail as follows:

$$\begin{bmatrix} X_g \\ Z_g \end{bmatrix} = \begin{bmatrix} -\sin\gamma_a & -\cos\gamma_a \\ \cos\gamma_a & \sin\gamma_a \end{bmatrix} \begin{bmatrix} L_w \\ D_w \end{bmatrix} + \begin{bmatrix} -\sin\gamma_{at} & -\cos\gamma_{at} \\ -\cos\gamma_{at} & \sin\gamma_{at} \end{bmatrix} \begin{bmatrix} L_t \\ D_t \end{bmatrix} \tag{4}$$

where the definition of γ_a and γ_{at} refer to Fig. 3 and nomenclature. The similarity for moment M is

$$M = M_w + M_t + \tfrac{1}{2}\rho V^2 S\bar{c}(C_{m0} + C_{m\delta_a}\delta_a)(1. + k_\mu F/G) \tag{5}$$

The deflection of flap δ_a remains constant during flight.

A nonlinear thrust model is based on the propeller theory and flight test[18]:

$$F = P_p/(V + V_0) + F_0 \tag{6}$$

The high-speed slipstream from the propeller has the influence upon the lift and moment, which is approximated as

$$L_F = L(1. + k_\mu F/G) \tag{7}$$

The induced downwash of the wing to the tail cannot be neglected. Since the time-varying downwash field is very complex, here it is approximated by a step function and a pure time delay (see Fig. 4). That is to say, the downwash step will reach the tail's neutral point after a time delay of τ_t

$$\tau_t = l/V \tag{8}$$

Therefore, the delayed downwash velocity is simulated as

$$w_{dw}(t) = V*[f_w 2S*C_A(t - \tau_t)/(\pi^2 b)] \tag{9}$$

where f_w is a factor dependent of the vertical position of the tail relative to the wing.

The assumption of aerodynamics will be discussed in the next part.

Modeling of the Unknown Transfer Function

In light of Newton's laws, the motion of an airplane is governed by forces and moments. Now the problem is how to describe the transfer function between turbulence and aerodynamic forces. Under the assumption of quasisteady aerodynamics, there is no difference between the generating process of aerodynamic forces caused by aircraft motion or by gust. But the unsteady effect distinguishes them from actual physical procedure. In Fig. 5 after a sudden vertical motion of the aircraft, say unit step α, the lift depends on the acceleration of the aircraft that results in the lift from noncirculation flow at initial moments (the so-called "apparent-mass" lift) as well as on the airspeed and state of motion that result in the lift from circulating potential flow.[20,21] When wake and free vortex $\Delta\Gamma$ leave far away behind the aircraft, the total lift reaches to its asymptote value. Owing to the inertia of aircraft, the time lag that is needed to approach the steady value of aerodynamics is comparably small relative to the aircraft's motion. However, after a sudden vertical change of front airflow, the same change of flow will gradually spread over the whole chord at the airspeed V. A stable distribution of vortex is gradually formed until all unital vortices $\Delta\Gamma_i$ are far away from the wing (see Fig. 6). That is to say, it takes time for the circulatory flow to reach its steady distribution. As mentioned earlier, the significant difference between both is that the latter has a "penetrating" procedure. In Fig. 7 the two typical transient procedures can be clearly seen for an example of two-dimensional airfoil, which were theoretically calculated by Küssner[11] and Wagner.[22]

The difference in unsteady aerodynamics leads to the following assumption of lift

$$L = L_{\text{plane}} + L_{\text{wind}} \tag{10}$$

The aeroelastic effect is neglected because of its small influence on vertical acceleration and angle of attack on the used aircraft and its difficulty to describe. Compared with the change of turbulence, the rigid motion of an aircraft is very slow because of the great inertia of airplane. In this way, the unsteady effect $L_{\text{wind,uns}}$ plays a more evident role than $L_{\text{plane,uns}}$. To concentrate the investigation on the subsystem between aircraft and turbulence, L_{plane} is under the assumption of quasisteady aerodynamics, and Eq. (10) becomes

$$L = L_{\text{plane},s} + L_{\text{wind,uns}} \tag{11}$$

The drag and moment have the similar forms of Eq. (11).

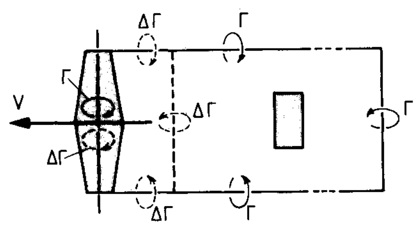

Fig. 5 Unsteady aerodynamic force caused by aircraft motion.

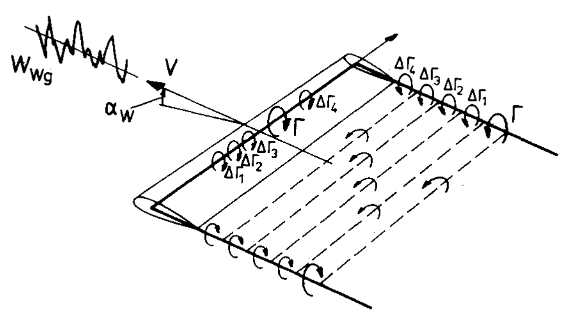

Fig. 6 Unsteady aerodynamic force caused by turbulence.

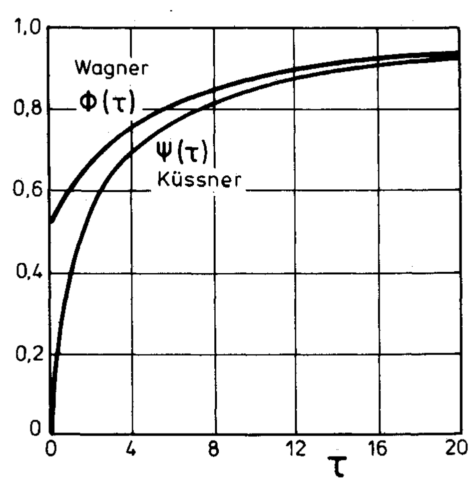

Fig. 7 Time histories of Küssner and Wagner function.

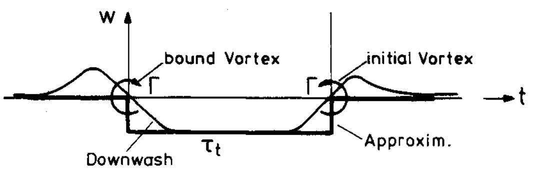

Fig. 4 Effect of downwash and its approximation.

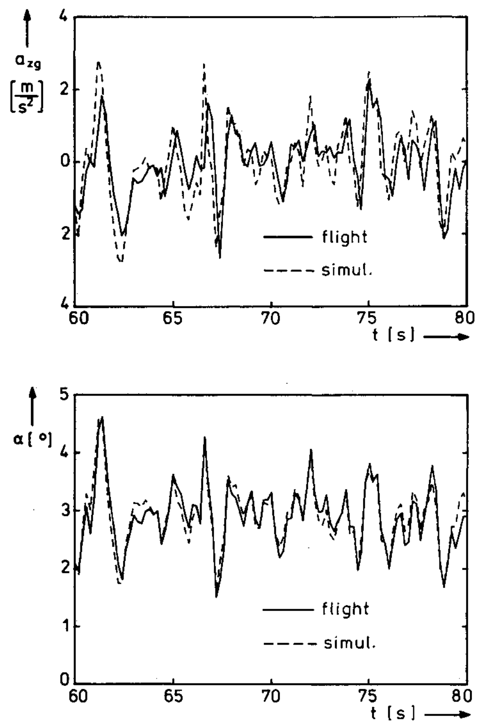

Fig. 8 Comparison between the flight test data and the simulation without considering unsteady effects.

Now we go further into the nature of the phenomenon: how turbulence generates the lift on aircraft. As stated earlier, the transient period is needed to allow all of the wakes and free vortices that are aroused during the wing's penetration, to move far away behind the wing after a sudden change of front airflow. This transition results in a time lag, during which lift is growing from zero to its steady value. Because turbulence changes quickly and at random, the time lag will be expected to be more evident. Figure 8 shows the comparison between flight-test data and simulation data without considering unsteady effects. The bound vortex changes are irregular at higher frequencies (see Fig. 6), and the wake and free vortex are correspondently generated and are left behind the aircraft at airspeed V. The lift on the aircraft at arbitrary time t should be superposed by the contribution of each bound vortex on the surface of aircraft, each free vortex, and each wake that distribute in different locations at this moment. In theory the solution can be found by solving Navier-Stokes equation with continuously varying turbulence as boundary condition. But today, even supercomputers are not fast enough to give the results in a reasonable time. As engineers, the powerful way to approach a problem is to describe the phenomenon by using the mathematically simplest model that matches the problem well. Of particular importance is the simplification based on the physical nature of the problem. From Fig. 8 the macrophenomena of the effect of turbulent atmosphere on an aircraft looks mainly like a time lag effect, which is the same as the previous analysis. Thus it is reasonable to assume the transfer function between aircraft and turbulence in the frequency domain has the following form:

$$G(s) = \frac{L_{\text{wind}}(s)}{\alpha_{\text{wind}}(s)} = L_\infty^\alpha \sum_{i=1}^{N} \frac{1}{T_i^* s + 1} \tag{12}$$

where $T_i^* = \bar{c}b_i/(2\,V)$, L_∞^α is steady lift caused by unit angle of attack. The form of Eq. (12) corresponds to the mathematical approximate expression of Küssner's function.[13]

For an aircraft passing a wind field, there is also a penetrating problem for the tail to undertake the same wind variation. Since unsteady aerodynamic effects occur locally at the wing and the tail, the horizontal tail passes the same wind field as the wing does, but delayed by a constant time τ_t calculated in Eq. (8) (see Fig. 9). In the present work, the time delay of the wind field and the downwash are treated the same in simulation.

Wind Measurement and the Aircraft's Equipment

The precondition of the strategy requires the precise measurement of the wind field along the flight path. From an aircraft, it cannot be measured directly. Only by taking the difference between the inertial velocity V_k and the true airspeed V, as shown in Fig. 10, the wind vector V_w along the flight trajectory may be computed[3] as

$$V_w = V_k - V \tag{13}$$

If V_k and V are precisely measured, the accuracy of V_w can be insured.

The Technical University of Braunschweig owns a research aircraft DORNIER DO128 (see Fig. 10) that is equipped with two turboprop engines and all of the necessary sensors to measure the inertial data and air data with high precision. The Inertial Navigation System (Honeywell Lasernav) is fixed on aircraft's body axes and located near the center of gravity. It includes accelerometers for all three body-fixed axes and gyros for the turning rates around these axes and for the Euler angles. Its sampling frequency is up to 50 Hz. The air data are measured by a five-hole probe on the top of a quite rigid flight-test nose boom, which is fabricated from high modular carbon fiber. The rotation speed of the propellers and their torques are indicated on some special instruments.

The measured signals can be processed on line by the onboard computer, which consists of a PDP 11/73 main computer and a VME-bus data acquisition computer. The data can be recorded digitally on a magnetic stream tape with 64 channels. Some selected signals can be monitored on line by the flight-test engineer for surveillance and error detection. The computer facilities on-board are capable of handling extensive online data processing with a sampling frequency of up to 50 Hz without data interface problems.

Since the work of on-line wind measuring began in beginning of the 1980s, the accuracy has been improved through the development of measuring techniques, such as dynamic inflight calibration, and the improvement of instruments, such as better sensors and greater capability of computer and data interface. Accuracy has been checked by using sensitivity and frequency spectrum analysis,[3,4] by comparison with tower measurement,[4] and, in the case of turbulent air,[23] by data compatibility check recently done in the Institute for Flight Mechanics of DLR. As a result, the accuracy of data used is

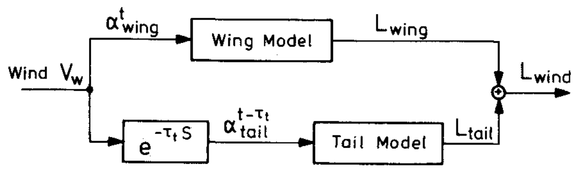

Fig. 9 Block diagram for the tail to penetrate the same delayed wind.

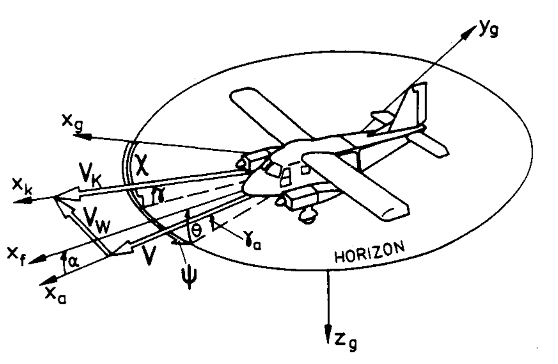

Fig. 10 Determination of the wind vector (from Ref. 4).

in the order of 0.3 ~ 0.5 m/s for both horizontal and vertical wind components. The time delay caused by the measurement and acquisition procedure has also been investigated.[24] The off-line correction of measured data is made before identification.

Parameter Estimation

Now the system identification is turned to parameter estimation. Past work in this area has been completed by applying maximum-likelihood or kalman filter or the least squares algorithms.[6,7,14,17,18]

In the present work, the performance index for the parameter estimation is defined to reflect directly the fitness of the assumed transfer function:

$$J = r_\alpha(\alpha - \alpha_m)^2 + r_{a_z}(a_{zg} - a_{zg,m})^2 \tag{14}$$

The parameter estimation is carried out by a powerful optimization algorithm[25] until J tends to be minimum under the all constraints above.

Results Analysis

All of the flight tests were made by the Institute for Flight Guidance and Control of the Technical University of Braunschweig with the research aircraft Dornier DO128. As an example, the fitness of the assumed unknown model was verified, and the validity of Küssner function was also tested.

First we used one first-order lag function, i.e., taking $N = 1$ in Eq. (12) to approximate the transfer function. After a transformation in the time domain, we get

$$L_{\text{wind,uns}} = L^\alpha_\infty Y_1(t) \tag{15}$$

where Y_1 is an argumented variable:

$$\dot{Y}_1(t) = [\alpha_w(t) - Y_1(t)]/T_1^* \tag{16}$$

Figure 11 shows the comparison of the flight data and the simulation with one optimized parameters ($N = 1$). The match between two curves seems favorable except at some peak points. To improve it, we take $N = 2$ in Eq. (12); in parameter estimation it was found that two parameters b_1 and b_2 are nearly the same. If Eq. (12) is expressed in form of nondi-

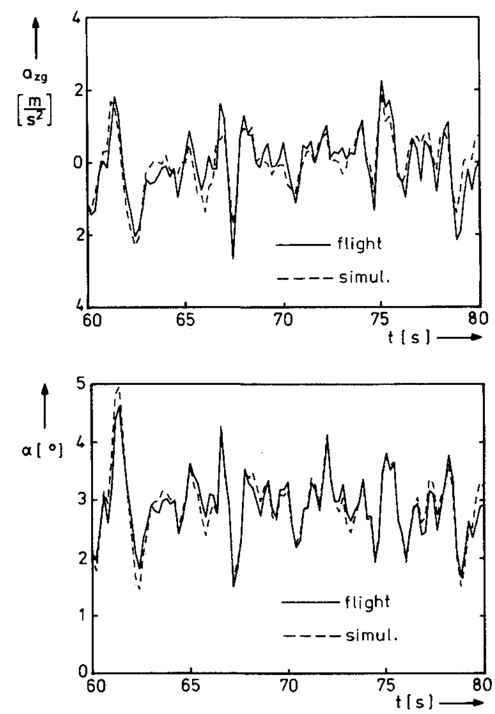

Fig. 11 Comparison between the flight test data and the simulation considering unsteady effects ($N = 1$).

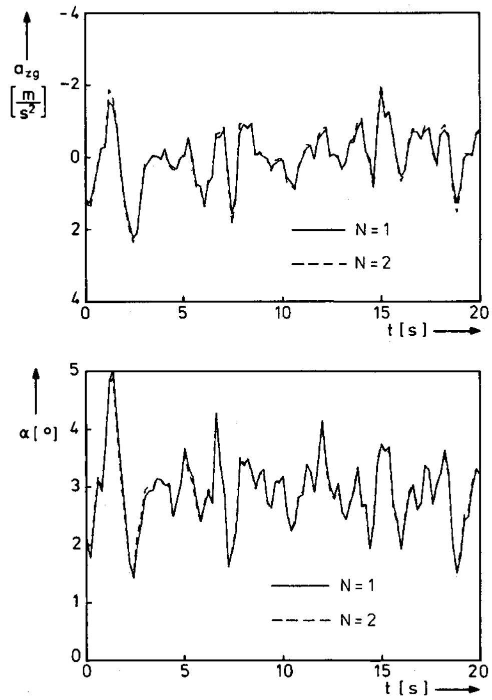

Fig. 12 Comparison between the simulation with different subsystem model.

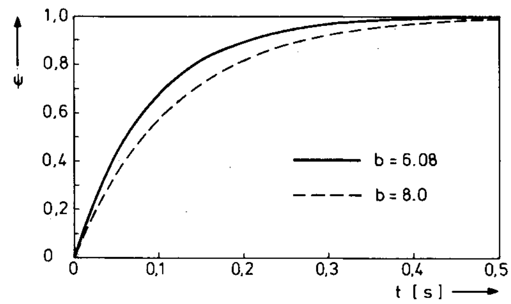

Fig. 13 Comparison between indicial response $\varphi(t)$ with different weighting factors and initial values.

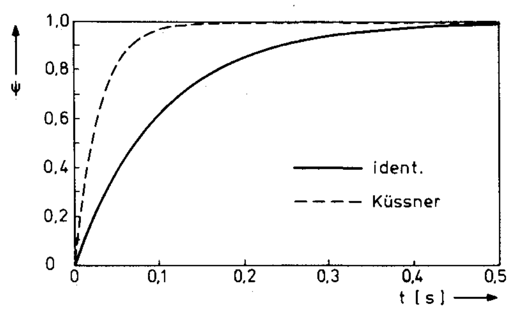

Fig. 14 Comparison of the indicial admittance between the known Küssner's function and identified results.

Table 1 Identified results with different flight-test data

Flight-test data	Weighting factor r_α	Weighting factor r_{a_z}	Identified parameter b_1
1	1.	1.	8.00
2	1.	1.	6.32
3	1.	1.	8.06
4	1.	1.	6.08
	0.	1.	7.49
			7.58
5[a]	1.	1.	7.58

[a]Different initial values.

mensional lift response to unit step sharp-edged gust, it changes to the form

$$\varphi(t) = 1. - \sum_{i=1}^{N} e^{-\tau/b_i} \qquad (17)$$

where $\tau = 2\ V \cdot t/\bar{c}$ is a nondimensional distance. For the two cases, $N = 1$ and 2, the comparison is demonstrated in Fig. 12, which shows almost no difference. As a result, $N = 1$ is better for its simple and sufficient accuracy in approximation.

As expected, it is the fact that the estimated results are almost the same, whatever different flight-test records or different initial estimated values are used. In Table 1, slight differences occur only when weighting factors or initial values are different. It is meant that the main effect of the black box can be well described by one first-order time lag function. From Fig. 13 the variation for different weighting factors and initial values can be seen, which makes no difference in the aircraft response.

A significant difference exists between the known coefficients of Küssner's function for finite aspect ratio $\Lambda = 6$ (Refs. 13 and 26) and the corresponding value identified here; if the response to a unit step sharp-edged gust is compared, see Fig. 14. The reasons why may be as follows:

1) The results from the simple lifting line theory has been found may be to be inaccurate for wings with finite aspect ratio,[15] and so, the practical precision of Küssner's function is doubted.

2) The neglected Wagner's effect on aircraft's flexibility may be one of the influential factors.

Conclusion and Suggestion

In view of the system theory, an aircraft has its inherent dynamic properties, which will be excited out by different external disturbances, hence a motion of an aircraft flying through turbulent atmosphere can be dissociated as the lower eigenfrequency motion and the high-frequency response to turbulence. This philosophy makes the complex problem simpler.

The transfer function of the subsystem between aircraft and turbulence for the longitudinal motion can be well approximated by one first-order time lag function in the frequency period of aircraft rigid motion.

The results show that this research aircraft has an additional time lag (T_l^*) of 0.1 s, which will include primarily the effect of unsteady aerodynamics and small influence of flexibility. It is more than three times greater than the value from the well-known Küssner's function.

The assumed transfer function is so simple that it will not increase much calculation when the model is included in conventional aircraft model to make synthetic parameter identification by flying maneuvers in turbulence. In addition, the robustness of the estimated aerodynamic derivatives will be expected to increase because the model now approaches closer to an actual aircraft.

The further work will be aimed to remove the other neglected effects, such as effects of flexibility, out of the above identified results, to reveal the practical validity of the theory. The influence of wind wavelength to the model parameter will be investigated too.

Acknowledgments

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