Development of Control Advisory System Using Future Wind Information

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In this research, cockpit instruments are being developed which aim to offer human pilots longitudinal control advice, considering predicted wind speed ahead. Future wind speed trends can be measured with an onboard Doppler LIDAR system developed by JAXA. Knowing about future wind changes enables the pilot to prepare slowly responding systems such as thrust in advance. This paper proposes a pitch and thrust advisory calculation method and a cockpit display to show the calculated advice to the pilot. Since the proposed system shows control advice to human pilots, it should be designed to be easily usable for them. The energy principle was chosen for the advisory calculation because of its intuitive concept and its ability to integrate thrust and elevator control when calculating the control advice; something which is not possible with the current separated autopilot and auto throttle systems. From the flight dynamics viewpoint, the basic equations of motions and the energy principle theory are extended to deal with the effect of wind when the advisory system calculates the required control inputs. Simulations were carried out to evaluate the advisory calculation with the energy principle and showed appropriate preparation for the expected wind shear is achieved with the LIDAR information.

Key Words: Control Advice, Cockpit Display, Human Pilot, Doppler LIDAR, Energy Principle

Nomenclature

Γ : Path angle
D : Drag
E_{tot} : Normalized specific total energy
“Total energy”
E_{dis} : Normalized specific energy distribution
“Energy distribution”
g : Gravitational constant
h : Height above runway
θ : Pitch angle
m : Mass
T : Thrust
τ_{L} : LIDAR range
V : Speed
W : Weight

Subscripts
a : Relative to the air
c : Command
ex : Excess
GS : Glide slope
g : Relative to the ground
L : LIDAR
ref : Reference
req : Required
tgt : Target
w : Relative to the wind

Abbreviations
AOM : Aircraft Operating Manual
FD : Flight Director
LIDAR : LIght Detection And Ranging
N1 : Engine rotational speed
(% of nominal value)
PAPI : Precision Approach Path Indicator
PFD : Primary Flight Display

1. Introduction

Today, aircraft themselves have much less problems during flights compared to those in the past as the technology in aeronautics has been highly developed. Therefore the main cause of air traffic accidents has shifted to disturbances in operation such as sudden turbulence.1) When an aircraft encounters severe turbulence, pilots need a certain amount of time to meet the required thrust because of the engine’s slow response however they can’t have sufficient time when turbulence is unexpected. Especially when a strong wind shear suddenly occurs, pilots’ workload rapidly increases and it can bring unwanted control, which leads to a dangerous flight. One possible solution for this problem makes use of Doppler LIDAR.2) It is an on-board equipment developed by JAXA and it measures wind speeds ahead which cannot be detected with the current weather radar. Using the wind information provided by the instrument, pilots will have enough time to prepare for an expected turbulence or a wind shear and as a result desired aircraft control can be achieved.

Previous studies have been done applying the LIDAR information mainly to auto pilot and auto throttle.3) However, in real commercial flights human pilots still perform take off and landing in which more skillful control is required than in other flight phases. Therefore, human pilots should also be considered when we try to develop a system for flight safety. This research aims to advise pilots about the desired control inputs. Future wind trend information detected with LIDAR will be used to calculate how much control inputs are required to prepare for the expected turbulence. A way to show the calculated advice to pilots will also be needed. Therefore, adaptation of a cockpit display called “Flight Director (FD)” will be studied. Although a modern aircraft already has an FD for pitch advice, its advisory calculation only considers current wind speed and not that in the future. Including future wind speed trend in calculation should play a crucial role to reduce risks in flight caused by severe turbulence. Also, the current pitch FD doesn’t consider thrust change though it affects the pitch dynamics. Integrative calculation of pitch and thrust advice should also be needed.

This research only focuses on the final approach phase to a runway. Also, only longitudinal dynamics will be studied so dynamics such as roll or yaw will be ignored.

2. Human pilots' control

Human pilots as objects of the control advice are the key of this research. The advisory calculation algorithm needs a different concept from that of auto pilot and auto throttle. Best control performance is not necessarily the best solution for human pilots. The factor that should be prioritized is whether human pilots can understand and follow the advice easily or not. In this section, it will be discussed how human pilots control an aircraft and what kind of advice they need. Important to notice is that the discussion is about a normal operation in the final approach phase for airline pilots, who fly with a large aircraft (B737 or larger). It might not be the case if they operate a smaller aircraft or a fighter.

2.1. Basics of pilots' flight control

It is important to know what pilots are doing in the cockpit in order to do research related to human pilots. This section provides a quick explanation about the basics of pilots' behavior in a cockpit. Readers who are interested in flight operation can find lots of information in Ref. 4).

Basically, pilots control two inputs for the longitudinal dynamics: a control column for the elevator control and throttle levers for the N1 control. N1 is the rotational speed of the engine's low pressure compressor. It is described as the percentage of the designed maximum rotational speed. While controlling, pilots continuously do "scanning", which is a way of looking at multiple cockpit displays in a certain order to obtain the indicated values. Pilots determine how much control column and throttle lever inputs are needed considering pitch, N1 and other flight states such as air speed and altitude deviation from the glide slope (reference altitude).

When the indicated pitch or N1 values are deviated from the target values kept in pilots' mind, they provide additional control inputs using the control column and the throttle levers. The target values are set by each pilot based on the flight situation and are often adjusted dependent on the environmental condition such as temperature and wind speed. Modern aircraft has a control advisory display called "Flight Director (FD)" for the pitch and roll advice. The display consists of two crossed bars and all the pilots have to do is to follow the crossed point using the control column.

2.2. Example case - air speed control

Imagine you are flying in the final approach phase and a wind shear (sudden tail wind increase of 10 kt) is measured with LIDAR. Probably, engineers try to design a controller such as a PID controller to keep path or speed precisely. However pilots don't necessarily think like that. Their priorities are the flight safety and comfort and one important way to achieve them is "envelope protection". It is a principle of control maintaining speed or pitch etc. within certain limitations to protect the aircraft from dangerous flight condition such as stall. During the final approach phase, pilots normally set the target air speed V_{tgt}, which is equal to or larger than the reference air speed V_{ref} established by AOM. V_{ref} is also larger than the stall air speed V_{s} containing safety margin. When a tail wind V_{L} is expected, pilots set the target air speed as $V_{\mathrm{tgt}} = V_{\mathrm{ref}} + V_{\mathrm{L}}$ in order to get speed margin so as not to stall even if the aircraft encounters the wind (Fig. 1).[*] Note that the operational limits are usually unsymmetrical: the lower limit allows less deviation from V_{ref} than the upper limit. This is because a lack of air speed directly leads to a loss of altitude which in the final approach phase means an increase of the risk crashing on the ground. Pilots also think in the same way as the operational limits to prevent negative deviations.

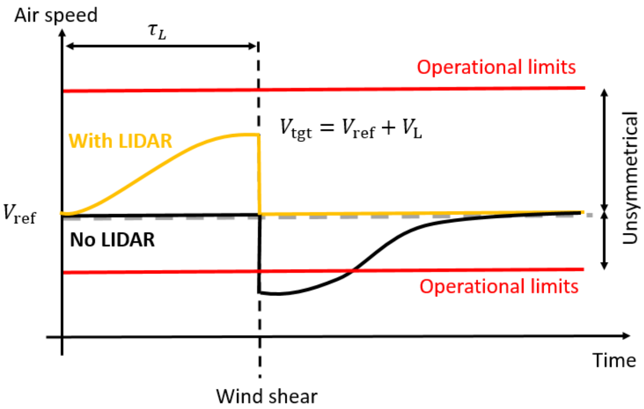

Fig. 1. Air speed schematic time history when a wind shear (tail wind) hits an aircraft. Pilots can maintain the operational limits with LIDAR by preparing air speed beforehand. τ_{L} is the LIDAR range.

2.3. Pilots' needs

Considering the discussion above, one can understand that pilots have different solutions from engineers. When pilots encounter a sudden wind, they try to keep the unsymmetrical operational limits for the flight safety by changing target values in advance to prepare a safety margin. Therefore they require the control advisory system to do calculations considering target speed setting and the asymmetry in the same way as they do and not in the way like a PID controller. In other words, the control advisory system needs to be easily understandable for pilots in order not to confuse them. If pilots can't see why the advisory system intends them to control in the way shown on the cockpit display, they will fall into confusion. It can cause lack of situation awareness and as a result a severe accident might happen. If the safety margin has been achieved, pilots can have spare mental capacity to enhance their situation awareness. Situation assessment and decision making are what human pilots are much better at compared to the auto pilot and auto throttle.

On the other hand, human pilots are inevitably not so good at precise control as auto pilot and auto throttle. Since they are not machines, pilots can't follow too fast or too precise control advice. Therefore, we should also be careful whether the calculated control advice is easily followed by pilots or not. The cockpit display design should also consider the followability. If the control advice is too complex, changing too quickly, or not presented in a convenient location, pilots' scanning work-

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[*] What pilots think about target speed setting is actually much more complicated. It differs depending even on the personality. The explanation in this section is simplified to avoid confusing the readers who are engineers and not pilots.

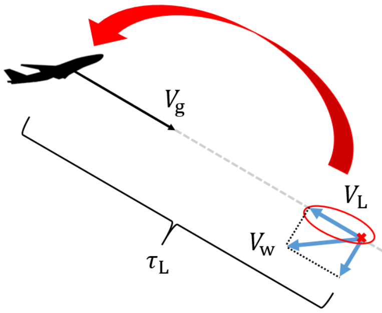

Fig. 2. Modeling of measurement by LIDAR. It can only measure the wind speed component V_L surrounded by the red circle. In this research, it is assumed that only the wind which is τ_L (s) ahead is used for the control advisory calculation.

load could increase and their control performance is expected to decrease.

3. System overview

3.1. Modeling of LIDAR

An onboard Doppler LIDAR is being develped by JAXA and its properties are mentioned in Ref. 2). This section explains the way the LIDAR is modeled in this research. First of all we should notice the LIDAR's main limitation[†]: it can only get the wind speed component in the direction of its optical axis (Fig. 2). Therefore, the wind speed information obtained with LIDAR is imperfect: the component perpendicular to the optical axis cannot be detected.

We also need to know that this research has four important assumptions regarding the data obtained by LIDAR.

- The LIDAR only measures wind speed at one point ahead, though the instrument can actually obtain wind speed information at several points.[2)]
- The LIDAR has a fixed time range τ_L and that it doesn't change even if the flight speed changes.
- The LIDAR can exactly measure the wind speed without noise.
- The wind field is not changing with time.

In order to examine how well the control performance of the proposed system is, it is necessary to assume such a simple and ideal situation as a first step. The number of measurement points will be expanded in the further research.

3.2. Concepts of the proposed system

The overview of the proposed system is shown in Fig. 3. The advisory calculator calculates required control input values using the wind speed information obtained by LIDAR and current flight state values such as current pitch angle and altitude. The calculated values will be shown on a cockpit display as control advice. Pilots obtain the displayed control advice while they are scanning (Sec. **2.1.**). Then they can control the aircraft with the control column and the throttle levers following the advice. This research mainly focuses on the part surrounded by the red box, which consists of two sub-parts. One sub-part is the advisory calculator and the other is the cockpit display for notifying pilots of the advice. In short, this research deals with both control theory and display design.

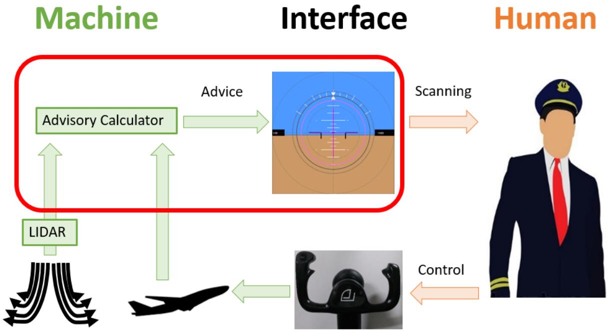

Fig. 3. Proposed system overview. This research mainly studies the part surrounded by the red box.

This research considers only longitudinal dynamics of the aircraft so that "desired control inputs" mentioned above mean elevator input and throttle lever setting. Pilots control these two input devices checking the current pitch angle, the N1 setting and other flight state parameters as discussed in Sec. **2.1.**. By showing the required pitch angle and N1 setting on a cockpit display, pilots can follow the advice and as a result desirable flight control will be achieved in the same way as the current pitch-only FD.

Although the current pitch-only FD has been highly developed, it only considers current wind speed and its rate of change for advisory calculation. Thus, the advice may be too late to control the aircraft stably and safely when it meets with sudden turbulence or wind shear. Especially for a large aircraft such as B747, the thrust response to the change of the throttle lever setting has large delay, so the control advice needs to be earlier. With the proposed system, pilots can know future wind change beforehand and therefore they have sufficient time to take the required action against the wind change even if the thrust has large delay. It is expected that shaking of the aircraft will be reduced and decision making whether a go around is needed or not will be conducted earlier.

3.3. Proposed cockpit display

As mentioned in Sec. **2.1.**, a modern aircraft already has pitch FD. The same display will also be used for pitch advice in this research, although the algorithm for calculating the advised value will be different. On the other hand, they are not equipped with a display to show thrust advice, which means an original display should be designed. When we recall the fact that pilots set the throttle lever position checking N1 values, we can understand that the required N1 values are needed to be displayed. Although in real flights pilots can set different N1 values for each engine, this research assumes that all the engines spin at the same rotational speed. In other words, only one N1 value is needed to be set and the other engines automatically spin at the same rotational speed.

Fig. 4 shows the proposed display for the thrust advice. We call it "Thrust FD". On the thrust FD, three thick circles are displayed. The magenta circle shows the required N1 value calculated by the advisory calculator. The black solid circle corresponds to the current N1 setting with the throttle lever while the black dotted circle indicates the current N1 value. These two black circles may not coincide because of the engine response delay. The bigger the circles are, the larger the indicated N1 values are. So, all the pilots have to do is to adjust the black

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[†] Not the limitation of the model.

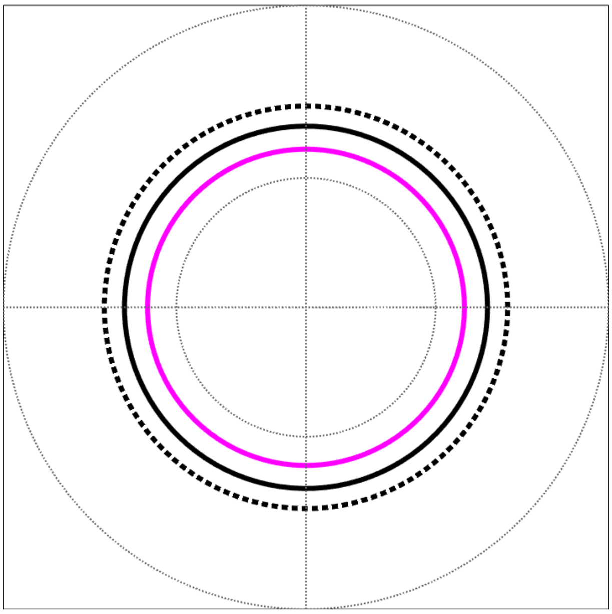

Fig. 4. Thrust FD.

solid circle to the magenta one using the throttle lever. Then, the black dotted circle gradually follows the black solid circle. Circle type of display is currently not common however it is expected to make pilots intuitively imagine the amount of the total energy, which is the basis of the advisory calculation (Sec. **6.**). Alternative designs such as bar indicators may be included in future studies.

Now, we have two kinds of FDs: the pitch FD and the thrust FD. The next problem to deal with is on which screen in the cockpit they should be displayed. As for the standard cockpit displays in front of a captain's seat, PFD is located to the left, on which pilots find current pitch angle and the pitch FD. On the other hand, current N1 setting is shown on EICAS, which is placed to the right across the navigation display. Although it can be possible to show the thrust FD on EICAS, such an arrangement forces pilots to look continuously to the right and left. Such an operation should make them irritated and following both of the two FDs is expected to be very hard. Considering these aspects, the authors propose an integrated display, which shows both of the two FDs on PFD (Fig. 5). We call it "Integrated FD". As a next research step, experiments with pilots should be needed to evaluate whether the proposed integrated FD is easy to follow and whether the circle display is the best solution.

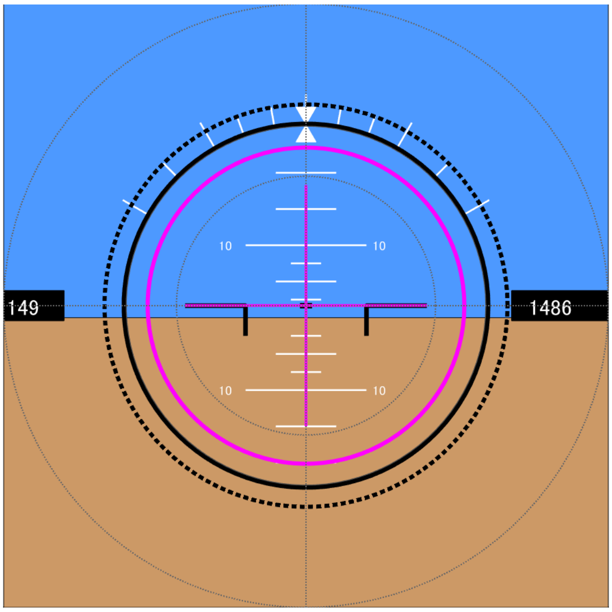

Fig. 5. Integrated FD.

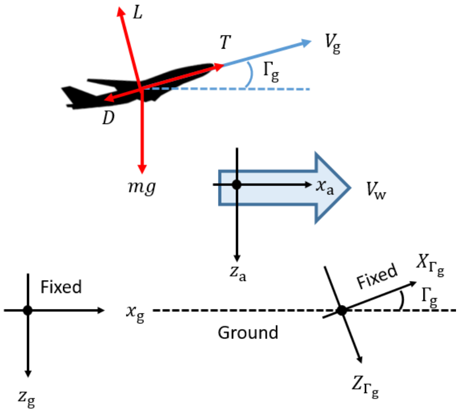

Fig. 6. Definitions of the dynamic systems. The wind is assumed to blow horizontally.

4. Augmented flight dynamics considering wind

If we aim to calculate control advice (required control inputs), we should properly understand flight dynamics. When considering a flight under wind condition, the difference between "ground speed V_g" and "air speed V_a" has an important meaning (Fig. 6). The former is measured in the ground-fixed system ($x_g - z_g$ system) and the latter means the flight speed measured in the wind-fixed system ($x_a - z_a$ system). Although they are exactly the same under no wind condition, they should be distinguished when we consider wind. Then the equation of motion should also be extended. When we regard an aircraft as a point mass,

$$m\frac{dV_g}{dt} = -mg\sin\Gamma_g + (T - D) \tag{1}$$

is the basic equation in the direction of $\overrightarrow{V_g}$ without wind effect. The angle Γ_g is "ground path angle" measured in the ground-fixed system, which should also be distinguished from "air path angle". When approaching a runway, we need to maintain a proper ground path angle (typically 3 deg) to ensure the aircraft touch down at the correct point. When there is wind around the aircraft, we have to rewrite the equation to make it consist of V_a instead of V_g because aircraft dynamics should be controlled considering the air flow. However, we will be faced with a problem then. The wind-fixed system is generally not an inertial frame so that Newtonian dynamics cannot be possible without an additional term on the right hand side. According to the classical mechanics, the additional term should be

$$-(\text{Mass}) \times (\text{Acceleration against the inertial frame}).$$

Then the equation should be rewritten as,[5)]

$$m\frac{dV_a}{dt} = -mg\sin\Gamma_g + (T - D) - m\frac{dV_w}{dt}\cos\Gamma_g. \tag{2}$$

Important to notice is that this derivation only considers horizontal wind and no vertical or side-wind components, which is sufficient for this research. If we transfer the last term on the right hand side to the left and apply the assumption of $\cos\Gamma_\mathrm{g} \approx 1$ based on the fact that the ground path angle is normally very small, we obtain

$$m\frac{d}{dt}(V_\mathrm{a} + V_\mathrm{w}) = -mg\sin\Gamma_\mathrm{g} + (T - D) \tag{3}$$

as a basic equation under the wind condition[‡]. When we compare this equation to Eq. (1), we can find a very simple relationship between the ground speed and the air speed.

$$V_\mathrm{g} = V_\mathrm{a} + V_\mathrm{w} \tag{4}$$

When there is no wind ($V_\mathrm{w} = 0$), the two speeds are the same ($V_\mathrm{g} = V_\mathrm{a}$) however they should be distinguished when we consider wind. Also, we can find that the right hand sides of the two equations Eq. (1) and (3) are the same, which means the dynamics are the same regardless of the measurement system.

5. Advisory calculation with the energy principle

In this section, the calculation of suitable control advice will be presented. Considering the aspects mentioned in Sec. **2.**, the energy principle is adopted for calculating desired control inputs (Ref. 6, 7)). It is a control theory which is formed from the viewpoint of mechanical energy. Based on the energy principle, thrust controls the total energy of the aircraft and elevator adjusts the energy distribution between the kinetic energy (air speed) and the potential energy (altitude). This simple principle is intuitive to human pilots so that they can easily understand what the proposed system intends for them to do. An additional benefit is that the energy principle provides both thrust and pitch control. Current auto pilot and auto throttle systems[§] work individually, though pitch and thrust control are coupled, which causes both systems to chase each other. The integration of thrust and pitch control solves the problem.

Eq. (3), the equation of motion considering wind, is the beginning for forming the advisory calculation with the energy principle. Since Γ_g is normally very small, we can apply the assumption $\sin\Gamma_\mathrm{g} \approx \Gamma_\mathrm{g}$ to Eq. (3). Then we obtain,

$$\frac{T_\mathrm{ex}}{W} = \frac{1}{g}\frac{d}{dt}(V_\mathrm{a} + V_\mathrm{w}) + \Gamma_\mathrm{g}, \tag{5}$$

with $T_\mathrm{ex} = T - D$ is the excess thrust, which can be used for flight control. From the mechanical energy perspective, this equation expresses the energy transformation law. The first and second terms on the right hand side respectively correspond to the time derivatives of the specific (divided by the weight) kinetic and potential energy normalized with air speed V_a.7) In this paper, the normalized specific kinetic and potential energy rates are called "kinetic energy" and "potential energy", respectively. The left hand side, which is the sum of the kinetic and potential energy, means the normalized specific total energy rate, which in this paper is called "total energy". Therefore, this equation expresses how the work of the excess thrust transforms into the kinetic and potential energies. Unlike thrust control, elevator control has a negligible influence on the amount of the total energy according to Ref. 6). It distributes the total energy determined by thrust into the kinetic and potential energies. Readers should notice that "kinetic energy", "potential energy", "total energy" and "energy distribution" are not exactly the "energy". They are the derivatives of the normalized and specific values. If they are multiplied with V_a and W and integrated with time, they become the "energy".

The longitudinal control advice should be for N1 setting and pitch angle as mentioned in Sec. **3.2.**. N1 can be derived from thrust with engine's performance data. The required control inputs can be described as

$$T_\mathrm{req} = T_\mathrm{tgt} + \Delta T_\mathrm{ex} \tag{6}$$

$$\theta_\mathrm{req} = \theta_\mathrm{tgt} + \Delta\theta. \tag{7}$$

As mentioned in Sec. **2.1.**, the target values T_tgt and θ_tgt are determined by pilots based on AOM. The additional values ΔT_ex and $\Delta\theta$, which are needed to deal with the wind ahead, should be calculated with the energy principle[¶]. To calculate the additional thrust and pitch as control advice, a PI controller is proposed in Ref. 6, 7). It will also be used in this research with some extension. The PI controller feedbacks the total energy

$$\dot{E}_\mathrm{tot} = \frac{\left(\dot{V}_\mathrm{a} + \dot{V}_\mathrm{w}\right)}{g} + \Gamma_\mathrm{g} \tag{8}$$

for thrust control advice and energy distribution

$$\dot{E}_\mathrm{dis} = \frac{\left(\dot{V}_\mathrm{a} + \dot{V}_\mathrm{w}\right)}{g} - \Gamma_\mathrm{g} \tag{9}$$

for pitch control advice. The forms of calculating additional values are as follows:

$$\frac{\Delta T_\mathrm{ex}}{W} = K_\mathrm{P}\left(\dot{E}_{\mathrm{tot}_\mathrm{ref}} - \dot{E}_\mathrm{tot}\right) + K_\mathrm{I}\int_0^t \left(\dot{E}_{\mathrm{tot}_\mathrm{ref}} - \dot{E}_\mathrm{tot}\right)dt + \Delta\dot{E}_{\mathrm{tot}_\mathrm{L}} \tag{10}$$

$$\Delta\theta = -K_\mathrm{P}\left(\dot{E}_{\mathrm{dis}_\mathrm{ref}} - \dot{E}_\mathrm{dis}\right) - K_\mathrm{I}\int_0^t \left(\dot{E}_{\mathrm{dis}_\mathrm{ref}} - \dot{E}_\mathrm{dis}\right)dt, \tag{11}$$

with K_P and K_I the controller's proportional and integral gains, respectively. The reference energies are formed with command values as $\dot{E}_{\mathrm{tot}_\mathrm{ref}} = \dot{V}_{\mathrm{g}_\mathrm{c}}/g + \Gamma_{\mathrm{g}_\mathrm{c}}$ and $\dot{E}_{\mathrm{dis}_\mathrm{ref}} = \dot{V}_{\mathrm{g}_\mathrm{c}}/g - \Gamma_{\mathrm{g}_\mathrm{c}}$. The first term of each of the forms correspond to the kinetic energy command and the second term the potential energy command. $\dot{V}_{\mathrm{g}_\mathrm{c}}$ and $\Gamma_{\mathrm{g}_\mathrm{c}}$ respectively mean acceleration command relative to the ground (time derivative of ground speed) and ground path command and are calculated as $\dot{V}_{\mathrm{g}_\mathrm{c}} = K_\mathrm{v}\{(V_{\mathrm{a}_\mathrm{tgt}} + V_\mathrm{w}) - (V_\mathrm{a} + V_\mathrm{w})\}$ and $\Gamma_{\mathrm{g}_\mathrm{c}} = \Gamma_{\mathrm{g}_\mathrm{tgt}} + K_\mathrm{h}(h_\mathrm{GS} - h)/(V_\mathrm{a} + V_\mathrm{w})$. The constant

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[‡] Strictly speaking, wind also acts as external force so that the drag D increases compared to no wind condition. Although this effect is considered in our flight simulations, it is ignored for simplification in the control advice calculations.

[§] In this paper, the term "auto throttle" is distinguished from "auto pilot", as is the same with the airline operation. The former controls the thrust and the latter controls the aircraft's attitude (pitch angle in this case) with the control surfaces.

[¶] T_tgt includes thrust component to compensate against the drag. T_ex doesn't contain such kind of component and therefore the subscript "ex" is put. Drag is assumed to be constant in this research regardless of altitude, speed and so on.

K_v has a dimension of "inverse of time (1/s)" so the form of $\dot{V}_{\mathrm{g_c}}$ shows the acceleration to correct the air speed error to the target air speed. The other constant K_h also has a dimension of "inverse of time (1/s)" and then the form of $\Gamma_{\mathrm{g_c}}$ says it is the additional ground path to correct the altitude deviation from the glide slope.7) According to the discussion above, the reference energies can be obtained:

$$\dot{E}_{\mathrm{tot_{ref}}} = \frac{K_\mathrm{v}\left(V_{\mathrm{a_{tgt}}} - V_\mathrm{a}\right)}{g} + \left\{\Gamma_{\mathrm{g_{tgt}}} + \frac{K_\mathrm{h}\left(h_\mathrm{GS} - h\right)}{V_\mathrm{a} + V_\mathrm{w}}\right\} \qquad (12)$$

$$\dot{E}_{\mathrm{dis_{ref}}} = \frac{K_\mathrm{v}\left(V_{\mathrm{a_{tgt}}} - V_\mathrm{a}\right)}{g} - \left\{\Gamma_{\mathrm{g_{tgt}}} + \frac{K_\mathrm{h}\left(h_\mathrm{GS} - h\right)}{V_\mathrm{a} + V_\mathrm{w}}\right\}. \qquad (13)$$

The authors have to mention that the control gains K_P and K_I have same values in both Eq. (10) and Eq. (11) to make PI controller parts converge with the same time constant. Also, $K_\mathrm{v} = K_\mathrm{h}$ because of the same reason. Therefore the controller parameters that we have to tune are K_P, K_I and K_v ($= K_\mathrm{h}$). The formalization discussed above are the application of what Ref. 6) proposed to our problem, introducing wind speed by $V \to V_\mathrm{a} + V_\mathrm{w}$ (see Eq. (4))‖.

Eq. (10) contains the third term $\Delta\dot{E}_{\mathrm{tot_L}}$, which has not appeared in the previous research. This term plays the role of controlling total energy based on the LIDAR information. For example, when a sudden tail wind (wind shear) is measured with LIDAR, the proposed system should provide advice to prepare for the expected wind shear by increasing speed and positive altitude deviation from the glide slope. Such kind of control advice intentionally makes the aircraft deviated from the target and balanced condition (target speed or flight on the glide slope for example) so it cannot be achieved with the former calculation concept. The wind speed obtained with LIDAR V_L affects this term and changes the total energy (in the sudden tail wind case, the term enhances the total energy to achieve both air speed increase and positive altitude deviation). The pitch control distributes the changed total energy into kinetic and potential energy. The mathematical form of the term $\Delta\dot{E}_{\mathrm{tot_L}}$ is relatively simple:

$$\Delta\dot{E}_{\mathrm{tot_L}} = \dot{E}_{\mathrm{tot_L}} - \dot{E}_{\mathrm{tot_w}} = \frac{1}{g}\frac{1}{\tau_\mathrm{L}}\Delta V_\mathrm{L}\left(1 + \frac{1}{2}\frac{\Delta V_\mathrm{L}}{V_\mathrm{g}}\right) \qquad (14)$$

where $\Delta V_\mathrm{L} = V_\mathrm{L} - V_\mathrm{w}$ is the difference between the LIDAR-measured wind speed V_L which is expected to hit τ_L (s) later and the wind speed currently blowing on the aircraft V_w. This form describes the error between the required total energy when the aircraft reaches the point at which the LIDAR measures the wind speed and the current total energy. The aircraft should prepare the total energy difference before going into the wind. If the expected wind speed V_L is large or the LIDAR range τ_L is small, the required total energy becomes large. When the aircraft doesn't have LIDAR ($V_\mathrm{L} = V_\mathrm{w}$), $\Delta\dot{E}_{\mathrm{tot_L}}$ is zero. The control system can be described with the block diagram shown in Fig. 7.

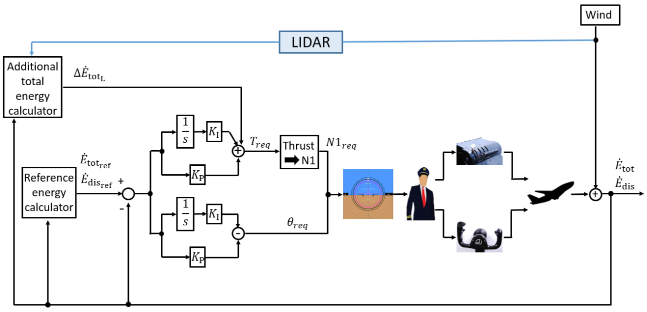

Fig. 7. Block diagram of the proposed system.

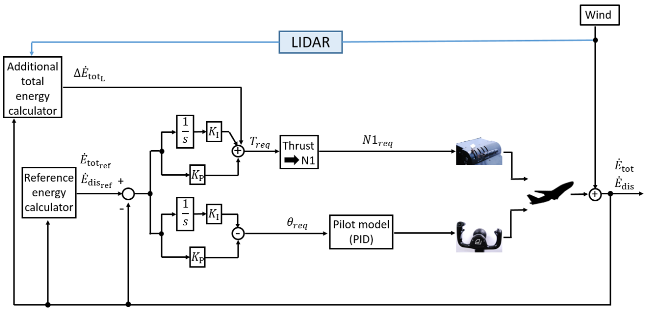

Fig. 8. Human pilot is not included in the simulation to evaluate the performance of the advisory calculation. PID controller is used for the pitch control. The throttle setting is automatically controlled.

6. Proof of concept with the energy principle

In this section, simulation results will be presented to evaluate how well the control advice works and how acceptable it is for pilots. The control advice with the energy principle is calculated by MATLAB (gains are in Table 1) and it is transferred to SimFlight, which is a software developed by The University of Tokyo for flight simulation to calculate the non-linear flight dynamics. It is also installed in the flight simulator owned by the Suzuki-Tsuchiya Laboratory at The University of Tokyo. Therefore, further simulation can also be done using the Lab's flight simulator with the same dynamics. Although the proposed system is intended to show control advice to human pilots, human-in-the-loop simulation won't be carried out now. As a first research step, it is too complex to adopt humans as a controller. Instead, a PID pilot model, which more precisely follows the advice than a human pilot, will control the pitch. As for the thrust control, the calculated required N1 is directly reflected the throttle lever setting, which is the same way as the auto throttle system. The block diagram for this simulation is shown in Fig. 8. If it is compared to Fig. 7, the difference can be easily understand. In this simulation, we will evaluate the performance of the advisory calculation with the energy principle. The human-in-the-loop simulation will be the further research step. The gains of the PID pilot model are listed in Table 2.

In this simulation, a B747 flies in the final approach phase (altitude: 2000ft - 100ft). The target values listed in Table 3 are trimmed without wind and these values are normal for a general final approach flight. The target pitch is kept fixed during the flight, while the target speed is changed dependent on the LIDAR information and the current wind. When the LIDAR detects the wind shear (sudden tail wind), the target airspeed is increased by V_L (kt) and it will be set to the initial value

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‖ Ref. 6, 7) feedback only $\dot{E}_\mathrm{tot}$ instead of $\dot{E}_{\mathrm{tot_{ref}}} - \dot{E}_\mathrm{tot}$ to avoid unwanted zeros of some transfer functions when the energy principle is adapted to B737. However in this research the type of aircraft is different (B747) so such kind of problem is not expected.

Table 1. Energy principle gains.

K_P	0.0015
K_I	0.000025
K_h, K_v	20

Table 2. Autopilot gains.

$K_{P,auto}$	5
$K_{I,auto}$	0.8
$K_{D,auto}$	1

Table 3. Situation settings.

Aircraft	B747
Weight	500000 lb
Flap	30 deg
Landing gear	Down
Initial altitude	2000 ft
Target airspeed	150 kt
Target pitch	1.42 deg
Target N1	63.3 %
Target ground path	-3 deg
Wind shear start time	40 s
Wind shear magnitude	10 kt (tail wind)
Direction of the wind	Parallel to the LIDAR's optical axis
LIDAR range	No LIDAR, 5s, 10s, 20s, 30s

(150 kt) again when the aircraft actually encounters the wind shear, which means $V_L = V_w$. The advisory calculation system has limiters for both of the control inputs N1 and pitch. N1 is limited within 50% $<$ N1 $<$ 80%, while pitch angle within -3deg $< \theta <$ 5deg. There is no wind when the simulation starts and 40 s later the aircraft suddenly encounters a tail wind increase of 10kt (Fig. 9). A sigmoid function is used for modeling this wind shear since the model needs to be smooth for calculation of V_w (Eq. (5), (8), (9)). This is a very simple model of wind shear. In order to examine how well the advice works under the ideal situation, the wind is assumed to blow just in parallel to the LIDAR's optical axis and has no perpendicular component. LIDAR can exactly measure the wind speed which blows τ_L (s) later on the aircraft. We will have simulation results of several cases, in which the LIDAR range τ_L is changed. Important notice is that only longitudinal dynamics is simulated.

Fig. 10 presents time histories of $\dot{E}_{tot}$ and $\dot{E}_{dis}$ (when τ_L =10), which are fed back to the PI controller and therefore are directly controlled by the energy principle (see Eq. (10) and Eq. (11)). We can see that it prepares for the expected wind shear by increasing the total energy. After losing the prepared amount of energies, both of the two energies finally converge to 0, though it takes some time. These graphs reveal that the energy control works well.

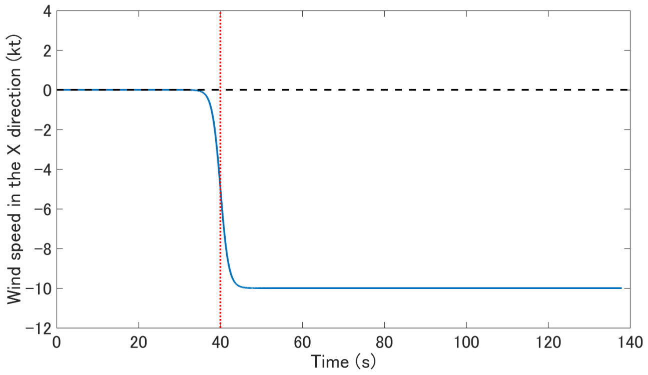

Fig. 9. Horizontal wind shear. Negative sign means tail wind and positive sign means head wind. The red line indicates the time when the wind shear starts.

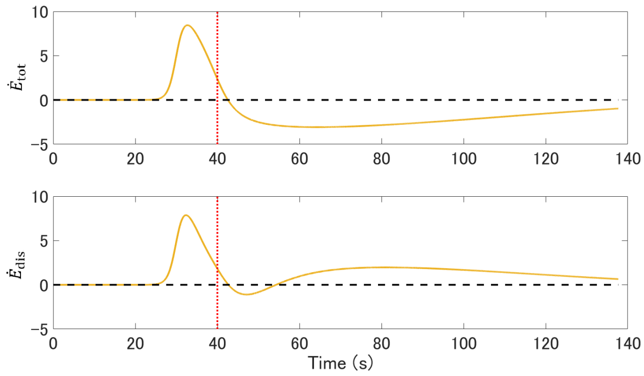

Fig. 10. $\dot{E}_{tot}$ and $\dot{E}_{dis}$, both of which are dimensionless, when τ_L = 10 s. $\dot{E}_{dis} > 0$ means energy distribution to kinetic energy. The dotted red line shows when the wind shear hits the aircraft.

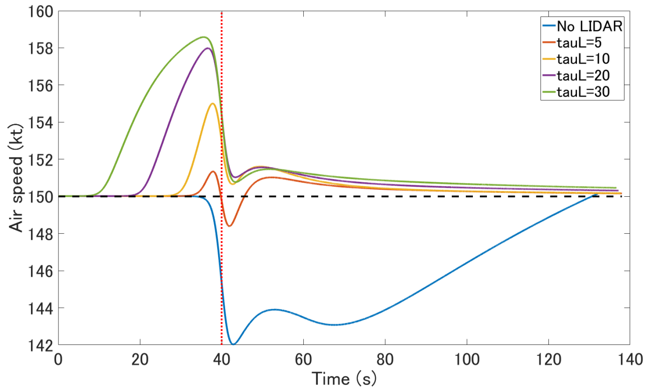

Fig. 11. Air speeds. The dotted red line shows when the wind shear hits the aircraft.

Fig. 11 shows the time histories of air speed V_a for each case. When the aircraft is not equipped with LIDAR, the air speed suddenly drops to around 142kt just after the wind shear happens, which should be avoided from the viewpoint of envelope protection. However when the LIDAR is used, the control advice prepares air speed margins for the tail wind and the air speeds don't decrease so much even when the wind shear occurs. This flight can be achieved owing to the additional term $\Delta\dot{E}_{tot_L}$. We can also see the wind speeds smoothly converge to the target air speed (150 kt). The LIDAR range τ_L affects the time when the preparation starts. If the range is too large, the advisory system prepares extra air speed. In this case, τ_L = 10 is enough for the preparation purpose.

Figs. 12 and 13 show the flight path time histories. Fig. 12 presents the altitude deviation from the glide slope and Fig. 13 depicts the approach angle to the touch down zone on the runway, which is the standard of the PAPI indication. The four black broken lines split the graph area into five. These areas correspond to the PAPI indications (number of white lights, number of red lights) = (0,4), (1,3), (2,2), (3,1), (4.0) from the bottom.[8] The aircraft should fly in the middle area (white, red) = (2,2). In the No-LIDAR case, the altitude greatly drops after the wind shear to the area of (white, red) = (0,4), which means it flies really low. Using LIDAR enables the advisory system to calculate ascent advice for preparation. As a result, the air-

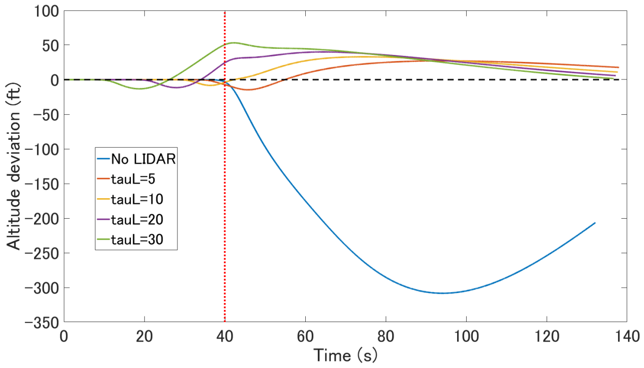

Fig. 12. Deviations from the glide slope. The dotted red line shows when the wind shear hits the aircraft.

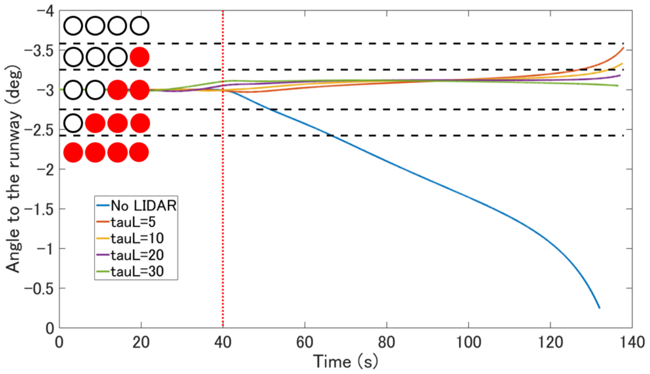

Fig. 13. Angle of approach to the runway. It is what is used for the calculation of PAPI. The black dashed lines divide the area into five, each of which corresponds to the five PAPI states. The corresponding PAPI indicators are shown on the left of each area. Pilots normally should fly within the area containing -3 deg (the reference path angle). The dotted red line shows when the wind shear hits the aircraft.

craft doesn't lose altitude and flies in the area of (white, red) = (2,2). However just after the LIDAR finds the wind shear, we can see slight altitude decrease. The reason why the advisory system calculates such kind of control advice is that a trade off between $\dot{V}_\mathrm{a}$ and Γ_g is inevitable when the energy principle is applied. Since $\dot{V}_\mathrm{a}/g - \Gamma_\mathrm{g}$ is fed back for pitch control advice (Eq. (11)), increase of $\dot{V}_\mathrm{a}$ and Γ_g are compatible. In this simulation case, the energy principle prioritized air speed increase to prepare for the expected loss and as a result Γ_g decreases slightly. In other words, the energy principle increases thrust so that it inevitably decrease pitch angle. However Fig. 13 reveals that the amount of the altitude loss is not so critical because the aircraft flies in the middle area (white, red) = (2,2). The longer LIDAR range prepares higher altitude but makes it converge rapidly into the glide slope altitude. The smallest altitude loss is achieved when the LIDAR range is 10 s.

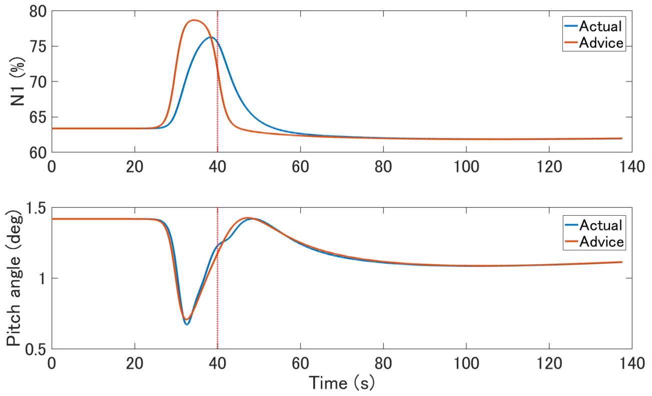

Fig. 14. N1 and pitch angle when τ_L = 10 s. "Advice" means they are the calculated values with the energy principle and "Actual" means the aircraft actually has the values at each of the time.

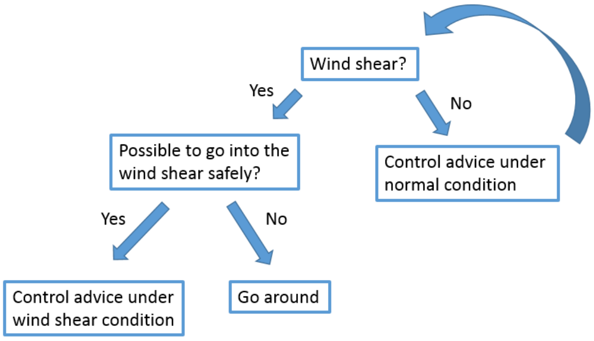

Fig. 15. Discrete control advice.

Fig. 14 shows time history of the controlled values N1 and Pitch when $\tau_\mathrm{L} = 10s$. "Advice" shows how much these of the parameters needs to be based on the energy principle. "Actual" shows how much values the aircraft actually performs. The graph clearly shows the system starts to prepare for the expected wind shear at around 30s, which is 10 s before it really hits. Each of the advice is within reasonable values and is smooth without rapid change. It is expected to be easily followable for human pilots. However, it might be confusing for them to make pitch down when it tries to increase thrust, though the amount is not so large (pitch down by 1 deg). It is also the consequence of feeding back of $\dot{V}_\mathrm{a}/g - \Gamma_\mathrm{g}$. We can also see thrust spin-up and spin-down delay in the N1 graph.

According to the discussion above, the simulation results clearly show the control advice with LIDAR using the energy principle works well, which meets pilots needs (Sec. **2.3.**). It can advise pilots to prepare air speed and altitude for the expected wind shear. The N1 and pitch advice may not be hard to follow. The followability should be confirmed with pilot-in-the-loop experiments.

7. Future works

As shown above, the energy principle works well in simulation. The next research step will be making the advisory system more suitable for practical application. One possible idea is to use LIDAR-measured wind speeds at several points. Using multiple wind information enables the system to know wind speed trend and it is expected to reduce unnecessary control advice. Furthermore, when the advisory system knows the future wind trend, judgment can be possible what kind of wind there is in front of the aircraft such as wind shear or turbulence. Our long-term goal is to make a discrete advice dependent on the situation and show pilots suitable control advice for each situation (Fig. 15). The integrated FD can also be developed. If it contains some more information such as speed trend vector or vertical speed indicator which can be cross-checked by pilots, the display becomes more easily understandable. Display designs for thrust FD other than circles may be considered.

Finally, experiments will be conducted using the flight simulator owned by the Suzuki-Tsuchiya Laboratory to evaluate the control advisory system and the cockpit display. A former professional pilot and several students will be expected to join the experiment.

8. Conclusion

A control advisory system is proposed for assisting pilots under the situation of encountering a turbulence including a wind shear. It uses wind speed information ahead measured with LIDAR for advisory calculation. The system enables pilots to prepare in advance for the predicted turbulence and it provides sufficient time for thrust to meet the required value, even though its response is slow. The energy principle is adopted for advisory calculation since it is intuitive to human pilots. New type of cockpit display called an “integrated FD” is also proposed to show the calculated control advice to pilots. Simulations were carried out to evaluate how well the advisory calculation with the energy principle using LIDAR information works. The results show that with LIDAR information the control system can avoid significant loss of both air speed and altitude.

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