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ESTIMATING TURBULENCE INTENSITY ALONG FLIGHT PATHS IN TERRAIN-DISRUPTED AIRFLOW USING ANEMOMETER AND WIND PROFILER DATA

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1. INTRODUCTION

Turbulent airflow due to disruption of prevailing winds by terrain may occur over the arrival and departure flight paths of the Hong Kong International Airport (HKIA) under certain weather conditions, such as strong east to southeasterly winds in stable boundary layer in spring, intense southwest monsoon in summer, and high winds associated with tropical cyclones.

Timely alerting of turbulence is crucial to assuring flight safety. In the existing Windshear and Turbulence Warning System (WTWS) operated by the Hong Kong Observatory (HKO), turbulence along flight paths, which is quantified in terms of the cube root of Eddy Dissipation Rate ($edr^{1/3}$) following international aviation practice, is estimated from the data of surface anemometers in the vicinity of the airport and on the hills nearby, based on correlation equations established from a limited number of turbulent flow events collected by a research aircraft before the opening of HKIA in 1998 (Neilley, 1995).

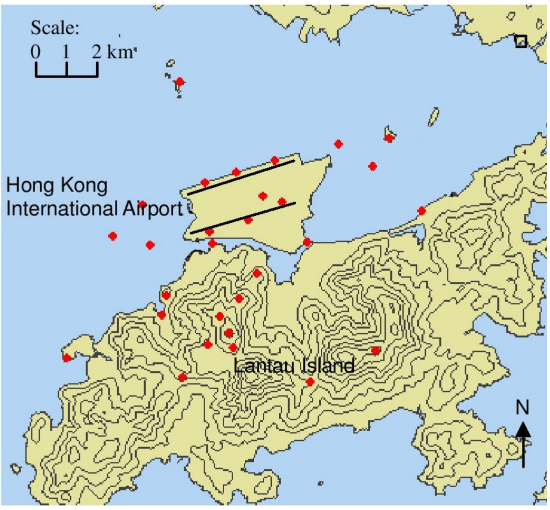

Figure 1. Topography around HKIA. Height contours are in 100 m

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This study revisits these correlation equations by using a larger dataset, namely, $edr^{1/3}$ derived from Quick Access Recorder (QAR) data collected onboard transport category commercial jets over a 2-year period at HKIA. The results of using additional data sources to establish the correlation equations, such as wind data from the newly installed anemometers at the valleys near the airport and the $edr^{1/3}$ in the upper air as estimated from wind profilers, are also presented.

2. ESTIMATING EDDY DISSIPATION RATE USING FLIGHT DATA

QAR data from a total of 832 arrival flights in 2006 and 2007 were used in the study. The types of aircrafts are listed in Table 1.

Type	Number of flights
A320	20 (20)
A330	439 (364)
B747	161 (150)
B777	212 (212)

Table 1 – Types of aircrafts and number of flights in the dataset. Numbers shown in brackets are the number of flights passing quality check.

The QAR data were processed by a software package developed by the National Aerospace Laboratory (NLR) of the Netherlands (Haverdings, 2000) for the calculation of $edr^{1/3}$. The data frequency of the $edr^{1/3}$ is 4 Hz. To characterize the turbulent condition during the approach of each flight, the ninetieth percentile point in the distribution of $edr^{1/3}$ is extracted for the period when the aircraft is around 3 nautical miles from touch-down to the end of approach. As heavy manoeuvres will produce incorrect $edr^{1/3}$ estimations, simple quality check was applied to the extracted $edr^{1/3}$ distribution and flights that produced suspicious $edr^{1/3}$ were discarded. Around 746 flights were eventually considered in the regression equations.

The flight data spanning a two-year period covered different seasons and different hours of the day in an operating environment. They should have advantages in terms of comprehensibility over the data from the test flights before airport opening. The operating environment dictated the runway usage for the approach and landing as shown in Table 2. Regression analysis for some sectors of the runway could not be performed since the respective dataset were too small to produce statistically meaningful result.

Figure 2. Runways and corresponding flight routes at HKIA. Runways such as 07/25 are named after their clockwise azimuth angle from the magnetic north. "L" or "R" respectively represents left or right facing that direction whereas "A" and "D" denote "Arrival" and "Departure" respectively.

Runway	Number of flights
07LA	380
25RA	320
07RA	35
25LA	8

Table 2. Distribution of runway usage for the quality-checked flight data in 2006 and 2007 .

3. ESTABLISHING ANEMOMETER BASED REGRESSION EQUATIONS

In the terminology of WTWS, each regression equation is called a regressor, which is a linear combination of predictors. Each predictor represents an individual type of wind observations obtained from anemometers in the vicinity of HKIA and on the hills nearby. The type of predictors used in the WTWS includes 15-minute mean wind speed (spd), wind speed standard deviation (sdev), and gust excess to mean wind speed (xs).

3.1 Selection of anemometers for regression

The weather conditions conducive to turbulent flow at HKIA could be characterized by the prevailing wind direction and the vertical stability of the atmosphere that produced a specific type of terrain disruption to wind flow (Neilley, 1995). These characteristic wind flow directions are defined as regimes. It is worth noticing that delineation of regimes is specific to each arrival and departure flight path as shown in Figure 3.

In the WTWS, regimes are defined based on the prevailing wind direction recorded at a relatively exposed and offshore anemometer, located at Waglan Island (denoted by "WGL" in Figure 4) . In this study, it was found that using some other stations, such as Sha Lo Wan (SLW) or Green Island (GI), whose locations are closer to HKIA, as the regime station yielded better regression results for some specific wind regimes. However, considering that the selection of a prevailing wind station should cater for different regimes of all runways, WGL is still adopted as the prevailing wind station or the regime station in this study. Figure 5 shows the distribution of wind directions at WGL for the flights using 07LA and 25RA. From the figures, it can be seen that the wind directions are not evenly distributed and therefore not all regimes defined for the flight routes can be covered in the regression study due to insufficient data. In this study, only regimes 030-090 and 090-210 for 07LA and regime 120-270 for 25RA are presented.

(a)

(b)

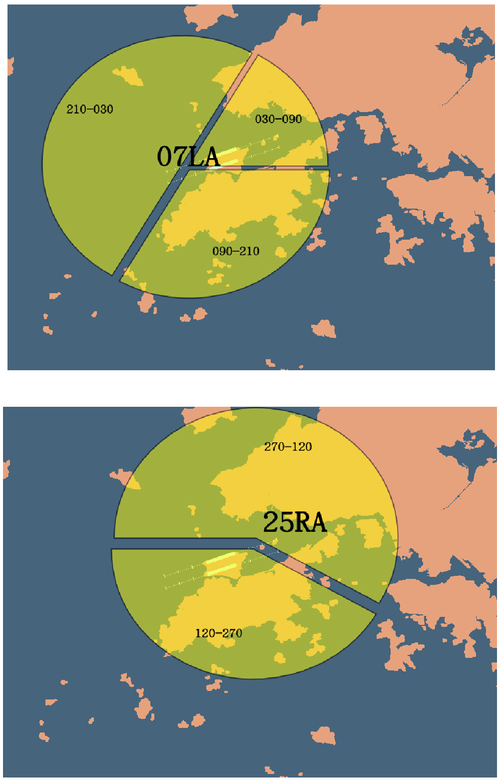

Figure 3. Examples of wind regimes defined for the runway (a) 07LA and (b) 25RA.

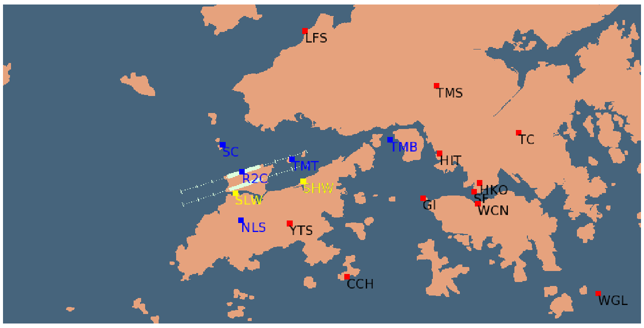

Figure 4. The location of the anemometers employed in the current WTWS (red), anemometers installed after the implementation of the WTWS (blue), and wind profilers (yellow) applied for establishing the regression equations in the present study.

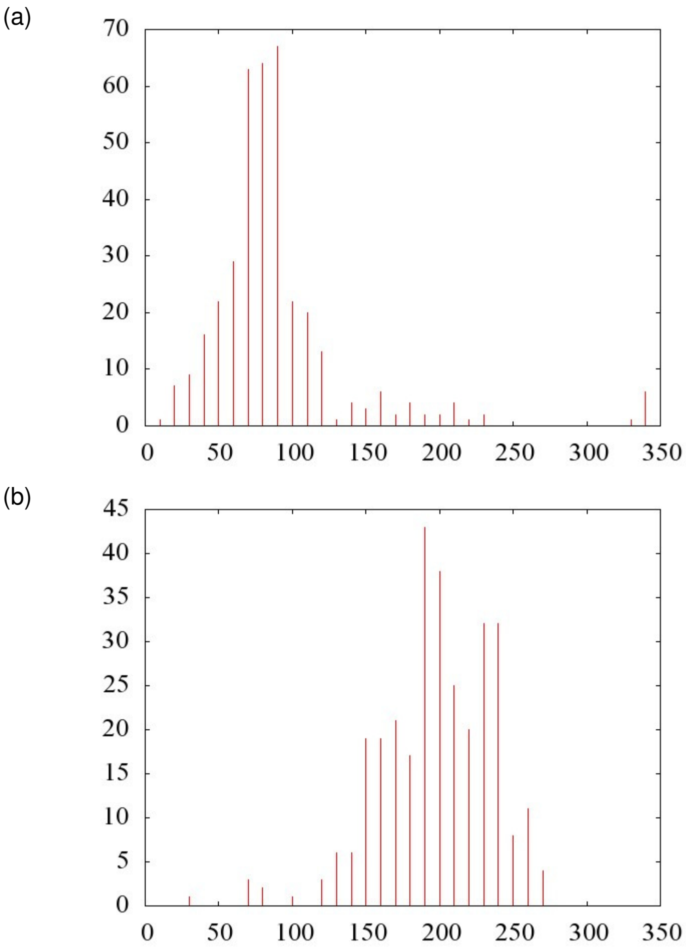

Figure 5. Distribution of wind directions at the regime station, WGL, for flights using (a) 07LA and (b) 25RA.

When selecting an anemometer to be included as a predictor, its location will be checked to see if it is exposed to the winds from the relevant regime. Then different wind observations from that anemometer will be correlated with the $edr^{1/3}$ observations to see if good relation could be found. The stations employed in this study include the anemometer stations currently employed in the WTWS (WGL, YTS, CCH, HKO, GI, HIT, SF, TMS, WCN, TC, LFS) and the stations installed after the implementation of the WTWS (R2C, NLS, TMT, TMB, SHW, SC), as well as wind profilers at SLW and SHW. The Locations of the above-mentioned anemometers and wind profilers are shown in Figure 4.

3.2 Single predictor regressor

Figure 6 shows a plot of $edr^{1/3}$ estimated from flights using 07LA with prevailing wind direction between 090 and 210 degrees against 15-minute mean wind speed at YTS (Yi Tung Shan, a hill station on the Lantau Island). The strength of turbulence along the approach to runway 07L is well correlated with the mean wind speed near the hill top of the Lantau Island. During the development of WTWS, mean wind speeds derived by averaging data over various time periods (e.g. 1, 5, 10, 15, 20 and 30 minutes) were tested and it was found that the regression result was not sensitive to the averaging period while 15-minute mean gave the best regression results. Apart from mean wind speed, standard deviation of wind speed and gust excess derived from anemometer data also exhibit good correlation with the strength of turbulence. Table 3 shows the top five single predictor regressors and the corresponding correlation coefficient (R).

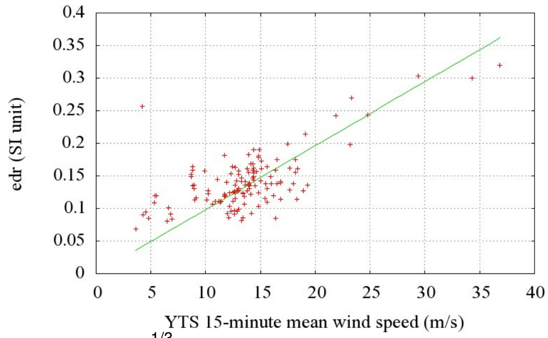

Figure 6. $edr^{1/3}$ against 15-minute mean wind speed at YTS (near a hill top on the Lantau Island). The correlation coefficient (R) is 0.68.

Station	Predictor	R
07LA regime 030-090		
YTS	spd	0.49
SLW	spd	0.49
NLS	spd	0.49
TMS	spd	0.48
LFS	spd	0.41
07LA regime 090-210		
GI	xs	0.74
GI	sdev	0.70
YTS	spd	0.68
CCH	spd	0.67
WCN	spd	0.60
25RA regime 120-270		
NLS	spd	0.68
CCH	spd	0.62
SHW	xs	0.60
TMT	xs	0.59
TMS	xs	0.59

Table 3. Top five predictors for the single predictor regression and their corresponding R values.

3.3 Single station multiple predictors regressor

The WTWS adopts a multi-linear regression approach with the selection of more than one wind observation from a station as predictors to predict turbulence for a particular runway through

$$edr^{1/3} = constant + \Sigma_i (A_i \cdot predictor_i)$$

The constant term is set to 0 so as to ensure that the predicted $edr^{1/3}$ will be 0 when there is no wind.

In the WTWS, each regressor has two predictors only. It might be due to the fact that inclusion of all the available predictors does not necessarily yield noticeable improvement. Table 4 shows changes in R with respect to the number of predictors used in the case of YTS. It can be seen that using more than two predictors does not gain significant improvement in the performance. Similar results were also found for other stations.

Predictor(s)	R
spd	0.68
sdev	0.47
xs	0.54
spd, xs	0.69
spd, sdev	0.69
spd, xs	0.55
spd, sdev, xs	0.69

Table 4. R values for different predictors used in the regressor for station YTS in 090-210 regime for 07LA.

Table 5 lists the top five two-predictor regressors and the R values while Table 6 shows some of the regressors currently used in the WTWS and the R values documented in the WTWS as compared with those obtained in this study.

Station	Predictor	R
07LA regime 030-090		
YTS	spd, xs	0.49
SLW	spd, xs	0.48
TMS	spd, xs	0.48
YTS	spd, sdev	0.47
TMS	spd, sdev	0.47
07LA regime 090-210		
GI	spd, xs	0.74
GI	sdev, xs	0.74
YTS	spd, xs	0.69
GI	spd, sdev	0.69
YTS	spd, sdev	0.69
25RA regime 120-270		
NLS	spd, xs	0.66
NLS	spd, sdev	0.66
TMT	spd, xs	0.63
TMT	spd, sdev	0.62
TMS	spd, xs	0.62

Table 5. Top five two-predictor regressors and their corresponding R values.

Station	Predictor	R	R (WTWS)
07LA regime 030-090			
YTS	spd, sdev	0.47	0.68
SLW	spd, xs	0.48	0.77
07LA regime 090-210			
YTS	spd, sdev	0.69	0.95
CCH	spd, xs	0.67	0.88
25RA regime 120-270			
TC	spd, xs	0.57	0.67
YTS	spd, sdev	0.58	0.64

Table 6. Comparison of R values between the present study and the existing WTWS.

The present study generally gives lower values of R as compared with those from the existing WTWS. It might be due to the fact that the flight data used in this study comprised different aircraft types instead of one research aircraft. In addition, the way of aircraft control might be different for a test flight and an operational commercial flight. The other source of discrepancy might arise from the algorithms in estimating $edr^{1/3}$ from the flight data. Notwithstanding the above differences, the results in the current study are similar to the previous study for WTWS in the sense that it would have suggested a similar set of anemometer wind observations as regressors. Besides, the results also revealed some promising new stations (such as NLS and TMT) which contributed positively to the regressor and could serve as additional regressors.

3.4 Multiple stations multiple predictors regressor

WTWS uses wind data from a set of anemometers, however, the regression algorithm only utilizes different wind observations from a single station, and combines the individual output from at least six stations (six independent regression equations) into one final predicted $edr^{1/3}$. It has the merit that the result will not be affected much if the operation of one or more of the anemometers failed. Here, the multi-linear regression method based on predictors from different stations was also tested and the results are shown in Table 7. The improvement is evident by comparing with the R values in Table 5. It is probably due to the fact that the new regressors containing independent wind measurements at different locations better represent the atmospheric conditions in the vicinity of the airport.

Predictor1	Predictor2	R
07LA regime 030-090		
NLS(spd)	HIT(xs)	0.57
YTS(spd)	HIT(xs)	0.56
R2C(spd)	HIT(xs)	0.56
YTS(spd)	HIT(sdev)	0.56
NLS(spd)	HIT(sdev)	0.55
07LA regime 090-210		
CCH(spd)	GI(xs)	0.86
CCH(spd)	GI(sdev)	0.86
CCH(spd)	GI(spd)	0.84
YTS(spd)	GI(spd)	0.83
YTS(spd)	GI(xs)	0.82
25RA regime 120-270		
GI(spd)	NLS(spd)	0.74
GI(spd)	NLS(spd)	0.74
GI(spd)	NLS(spd)	0.74
YTS(spd)	GI(sdev)	0.73
GI(spd)	TMB(spd)	0.73

Table 7. Top five two-predictor regressors using predictors from different stations.

Along the same line, a three-predictor regression formulation was also established. While improvements could still be found, the combination of predictors in the best regressors appears to bear lesser physical meaning and become merely for the purpose of data fitting.

4. WIND PROFILER DERIVED EDDY DISSIPATION RATE

Two wind profilers were installed in the vicinity of HKIA (Yeung, 1998), namely at SLW and SHW. Wind profilers retrieve winds at various altitudes above the ground by detecting movements of eddies in the atmosphere using radio signals. Software packages are available for estimating $edr^{1/3}$ from the returned signals. The NIMA2 package (Morse, 2002) was adopted to extract the mean and maximum $edr^{1/3}$ below 500 m. The estimated values of $edr^{1/3}$ were then compared with those from QAR measurements and the results are shown in Table 8.

Predictor	R
07LA regime 030-090	
wSHW edr (mean)	0.03
wSHW edr (maximum)	0.07
wSLW edr (mean)	0.33
wSLW edr (maximum)	0.36
07LA regime 090-210	
wSHW edr (mean)	0.00
wSHW edr (maximum)	0.00
wSLW edr (mean)	0.25
wSLW edr (maximum)	0.26
25RA regime 120-270	
wSHW edr (mean)	0.39
wSHW edr (maximum)	0.38
wSLW edr (mean)	0.41
wSLW edr (maximum)	0.44

Table 8. Regression results based on wind profiler derived $edr^{1/3}$.

By comparing the R values in Table 8 and Table 3, it can be seen that correlation between $edr^{1/3}$ estimated from wind profilers and those estimated from the flight data are relatively weak.

5. CONCLUSIONS

The HKO operates the WTWS for HKIA and part of the system uses a set of anemometers based regression relations to estimate the strength of turbulence along the approach and departure flight paths. The regression relations were derived from $edr^{1/3}$ recorded by a research aircraft through a number of test flights over HKIA. This paper reviews the regression relations using flight data from commercial jets collected in a 2-year period of 2006 and 2007. The estimated turbulence along the flight paths quantified in terms of $edr^{1/3}$ were calculated from the flight data using NLR package and analysed against wind observations from various anemometers in the vicinity of the airport.

The study results are generally similar to those documented in the WTWS, although the goodness of fit is not as good as the latter. The discrepancies may arise from different aircraft types and the algorithm for calculating $edr^{1/3}$. Study results showed that a number of new anemometers which were installed after the implementation of the WTWS, such as TMT and NLS, contributed positively to the regression model and could serve as additional regressors for turbulence estimation. Besides, the multi-station multi-linear regression method gave better results than the single station multi-linear regression model currently used in the WTWS.

The values of $edr^{1/3}$ in the upper air as estimated from wind profilers in the vicinity of HKIA were also examined but their correlations with those estimated from the flight data were found to be relatively weak.

In the next step, direct comparison between the results from the new regression equations in this study with those adopted in the existing WTWS will be made.

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