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A SUBJECTIVE EVALUATION METHOD OF AIRCRAFT VIBRATION IN FLIGHT TEST

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Abstract

In flight test aircraft abnormal vibration occurs due to test maneuver, test environment and aircraft configuration during development. The abnormal vibration may cause annoyance, discomfort, interference with crew activities, impaired health or motion sickness, especially for the new designed aircraft. Each abnormal vibration event needed to be carefully evaluated before next sorties. There are two kinds of data may contribute to vibration evaluation, one is the data from instrumentation such as accelerometer,strain gauges etc, however they are not always available due to limited test resources. The other data is the test crews' comments to the vibration phenomenon, typical comments are highly subjective qualitative description of how one feels, to establish a standard or rating system is the most practical solution. The most of the existing subjective rating method focus on crew comfort only and were based on studies in controlled lab environment or simulation, test results have to be extrapolated to real flight. In this study, a 10-points rating scale method with coverage of all possible effect of vibration including safety, crew activates and comfort was developed following Cooper-Harper handling qualities rating format, meanwhile the exposure time was also been considered in the evaluation criteria. By the standardize rating method crew subjective feeling or comments to the vibration events were derived to more useful quantitatively information to aid decision making during flight test.

Keywords: Vibration, Subjective Evaluation, Rating Scale, Flight Test

1. Introduction

Aircraft vibration event happened frequently in flight test, especially for the new designed aircraft, certain vibration can be expected to be normal like transient vibration during landing gear extension, vibration when speedbrake deployed, however there are also some abnormal vibration which cause annoyance, discomfort, interference with crew activities, impaired crew health or motion sickness[1]. Each abnormal vibration needed to be carefully evaluated before next flight to ensure safety during flight test. There are two kinds of data may contribute to vibration evaluation process. One is the objective data from instrumentation such as accelerometer, strain gauges, video/audio etc., however these kinds of data are not always available due to limited test resources. The other data is the test crew subjective feeling or comments which are always available to support decision making in flight test.

Most of the vibration evaluation studies focus on objective side, the criteria for objective are industry standard such as ISO 2631, GJB 67.8A. The pilots' comments are highly subjective qualitative description of how one feels, to establish a standard or rating system is most practical solution. Although rating method of varies form have been used for evaluation of vibration problems, deficiencies of these method are apparent. Firstly, most subjective rating methods were studied in controlled lab environment or simulation. The lab test result has to be extrapolated to real flight. Secondly, most of the existing methods focus on crew or passages comfort only. Thirdly the rating scale are not well formed or to be pure subjective rating, the ambiguous definition of the scale cause gap between flight test team and design team. With the existing methods, it is difficult to understand the nature and effect of vibration for the design engineers, thus has very limited help for manager to make decision of design change or take actions to control the vibration. As Flight Test Engineer been a connection between test pilot and designer, we developed a method of 10-points scale following

Cooper-Harper handling qualities rating format which is familiar to test pilot. This method has clearly defined meaning of each scale, so that test pilots and designers has common understanding. Engineering action to each of the scale was established to provide an agreement between test team and engineering team to assist test program management.

2. Considerations of Subjective Evaluation Method

2.1 Human Response to vibration

A vibration can be specified as function several variables including frequency, direction, duration, amplitude. There are many researchers study the relationship of vibration variable and human response[1], some of the important points are listed below.

Response to vertical vibration:

<0.5Hz motion sickness; sweating, nausea, vomiting

<2Hz eye able view object moving with body or to compensate look at non-moving objects
free movement of hand disturbed, hand position activities interference

\>2Hz amplification vibration in body

5Hz transmissibility of vertical vibration to head is max, interference with hand activities greatest, cause greatest discomfort

Response to horizontal vibration

<1Hz sway

1~3Hz difficult to stabilize upper part of body/ discomfort greatest

\>10Hz most vibration felt at contact point

The effect of vibration exposure time t, vibration amplitude a to comfort are expressed in equation(1) and equation(2):

$$a^4 t = constant \quad (1)$$

$$a^2 \propto comfort \quad (2)$$

To define a subjective rating method of vibration, it is necessary to consider these variables and understand the basic relationship of vibration variables and human response.

2.2 Characteristics of Subjective Evaluation Method

It is difficult to measure pilot’s opinion than aircraft characteristic. The subjective rating scale is most used tool, it is wildly used in almost every aspect of ergonomics research and practice for assessment of vibration, fatigue, comfort[2]. A rating scale can minimize disagreement between test crew. The rating itself has little meaning; it has to be referred to comments of flight test crew i.e., the description of the vibration phenomenon accrued during flight test. A typical description is about how crew feel the vibration including comments on vibration severity, duration, direction, frequency, amplitude, the effect and the condition when vibration happened. The most of objective evaluation methods need to install sensors then conduct flight test at condition which vibration event happened to gather data. The subjective method has two benefits over objective method, i.e., much lower cost and availability. The main disadvantage of subjective method is the accuracy which can cause by individual difference in perception of vibration. Sometime it can be ambiguous due to the qualitative natural. A rating method can turn qualitative comment to quantitative data and with same understanding of the rating system, individual difference can be minimized. It should be noted that necessary training of usage of rating method is also important.

2.3 Special Consideration in Flight Test

Aircraft under flight test especially the new design aircraft, aircraft configuration that during development can be a cause of abnormal vibration. Unlike airliner operations, flight test operate aircraft in a very different way, the test maneuver or test condition can be a cause of vibration, for example sometime you may find stronger vibration at certain taxi speed range that airliner operation rarely taxi at. Most of flight test maneuver is conducted under manual flight with the pilot in loop, aircraft vibration and pilot body coupled can result in biodynamic issue during flight test. The vibration event may affect safety and need to be evaluated before next flight, test manager needs information to make decision whether continue or stop test. In a situation that no vibration sensor data is available, the crew’s subjective evaluation become the key to decision-making.

2.4 Issues of existing methods

The International Standard (ISO 2631) for evaluation of human exposure to whole-body vibration gives guidelines for how vibration affect human, Short-term effects include annoyance, temporary hearing threshold shift (temporary hearing loss), reduced motion control, impaired vision, discomfort and fatigue. Long-term and extended exposure to whole-body vibration has been linked to chronic back pain. In short, vibration effect on human performance and health, it interferes with comfort, activities, and heath, however most of subjective method focus on comfort only.

The study of Saab 2000 aircraft vibration defined a 5-scale rating from 1 means pleasant to 5 means unpleasant[3]. A four-level rating scale was developed in controlled lab environment[4]:definitely, perceptible-mildly, annoying-extremely and annoying-alarming. These examples show the issue of most existing method i.e. lack of a clear scale definition and focus on comfort only. Another study shown several events encountered in cockpit vibration due to elastic mode fed back into flight control stick through involuntary motion of the pilot upper body and arm[5]. In this case, the vibration affects pilot ability to maneuver, three different scale were used to evaluate the affect, including a 6-scale ride quality rating in Table 1, a 6-scale control rating in Table 2 and Cooper-Harper for handling qualities. The influence definitions are listed in Table 1 and Table 2. To improve the existing methods, we will develop the a 10-points scale considering all possible effect of vibration to human.

Table 1 Rating for Ride Quality

Base Influence on Ride Quality	RQR
Cockpit vibrations do not impact ride quality	1
Cockpit vibrations are perceptible but not objectionable - no improvement necessary	2
Cockpit vibration are midely objectionable - improvement desired	3
Cockpit vibration are moderately objectionable-improvement warranted	4
Cockpit vibration are highly objectionable- improvement required	5
Cockpit vibration are abandonment of task - improvement required	6

Table 2 Rating for Pilot Control

Base influence on pilot control input	CIR
Pilot does not alter control input as a result of aircraft flexibility	1
Pilot intentionally modifies control inputs to avoid excitation of flexible modes	2
Cockpit vibrations impact precision of voluntary control inputs	3
Cockpit vibration cause occasional involuntary control inputs	4
Cockpit vibration cause frequent involuntary control inputs	5
Cockpit vibration cause sustained involuntary control inputs or loss of control	6

3. Scale Development

3.1 Scale Definition

The first question is about safety. In Cooper-Harper the worst case is lost control or safety concerned. For vibration, three level 10/9/8 are defined concerning safety, because it is more complex for vibration than handling qualities and the action needed is also varies. Crew choose the appropriate level of aircraft failure or crew injury to determine the rating as shown in Figure 1. It can be either aircraft damage or crew injury that already happened or not happened yet due to limited exposure time, but crew make judgement that it may cause safety issue in prolonged exposure time. In flight test once serious vibration happen pilot would take immediately action to prevent it from happening in most case. The objective facts, crew feelings and exposure time are considered in the evaluation criteria.

The next question is about activates. Activates in flight test environments includes flight operations

side-stick control, pedal control, reading of instrument, hearing and seeing, communication with radio and crew, conducting flight test maneuvering etc. Rating of 7 means unable to continue or cause of abandon of certain activities such as test point conduction due to unacceptable level of vibration, or unable maintain required test condition/performance such as speed and altitude tolerance. Rating of 6 means crew can continue activities but with difficult and lot compensation required. Rating of 5 means crew can perform normal task but with increased workload in the vibration environment.
The last question is about comfort, one can choose 2/3/4 base on appropriate level of discomfort. Half points such as 3.5, 2.5 can be added to specify more detail levels of comfort.
The last option in Figure 1 is rating of 1 which means no affects. So, in this 10-points scale, there are 9 points on the negative side. According to the NASA study[6],uni-polar scales containing either 7,9 scale points provide the greatest reliability. The NASA tests indicate subject generally use only one portion of the bipolar scale associated with discomfort. This new scale adapt the NASA research results, 9 points(2-10) are on the negative side, for the main objective of flight test is to find problem. The full definition of the rating scale is shown in Figure 1.

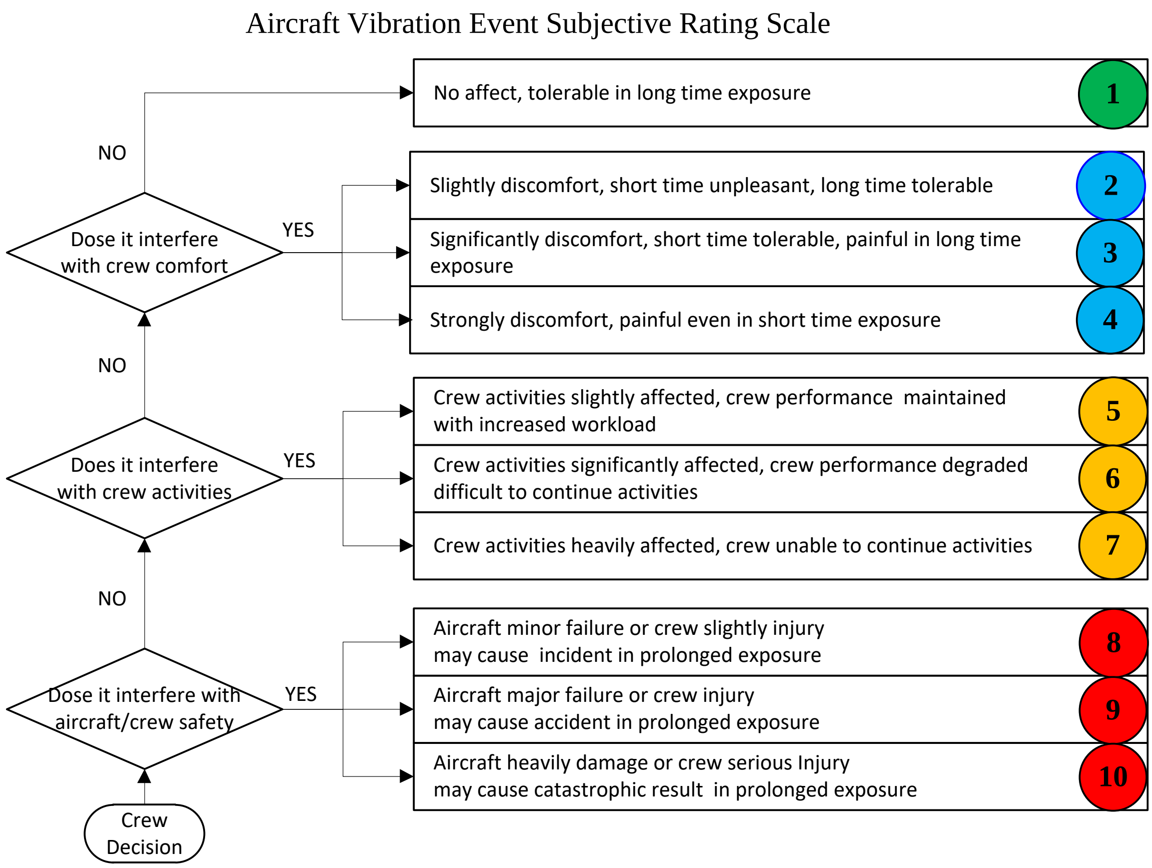

Figure 1 – Aircraft Vibration Rating Scale Definition

3.2 Subjective Level Determination and Corresponding Engineering Action

If a vibration event affect crew comfort, activities or safety, then the rating should be determined by the worst case. The rating must correlate to comment, rating itself mean little to design engineer. For normal vibration such transient vibration during landing gear operation, which has no adverse effect no need to record and evaluate. The evaluation should be conducted after recovering from the vibration if possible and must not affect flight safety. It is also important that final decision should refer both subjective opinions, objective facts as well as aircraft ground inspection results.

The final rating level for a vibration is determined by the worst effect as shown in equation(3).

$$L = max\{comfort1\ comfort2...,\ active1\ active2\ ...,safety1\ safety2...\} \quad (3)$$

The purpose of vibration evaluation is to help locate the vibration causes and solve the problem. To solve the problem, full information about the vibration event is necessary. The flight test crew determine the rating level, also provide comments on the how the vibration affect comfort, activities or safety. Based on the ratings, engineering actions required are defined as in Table 3.

Table 3 Engineering Action Corresponding to Rating

L	Engineering action
1	No action
2	Record
3	Record and analysis data
4	Record, analysis data and determine vibration source for further evaluation
5	Record, analysis data, determine vibration source, vibration should be controlled
6	Record, analysis data, determine vibration source, vibration should be improved
7	Record, analysis data, determine vibration source, vibration must be improved
8	Aircraft flight should be limited to vibration free envelope until problem solved
9	Aircraft not allowed for flight until problem improved
10	Aircraft not allowed for flight until problem solved

4. Application in flight test

4.1 Taxi vibration

In a taxi test of a civil aircraft, after three trials with maximum speed 5kn, the test was aborted for vibration was too strong to continue. Pilot's comment was that after applying brake at 2-5kn, aircraft immediately build strong lateral vibration in cockpit.

FTE rated as 8, test pilot rated as 9, the vibration had not caused structure damage, crew made judgment that if continue test, it might cause nose gear damage which would be a major failure.

Further analysis after the test shown it was cause by brake malfunction, engineering analysis results was consist with crews' comments. The aircraft flight test was suspended until brake software upgraded to solve the problem.

This example shows that even for a normal low speed taxi test, serious vibration event that affect safety may happen. It proved that defining a rating scale considering safety factors are necessary in flight test.

4.2 Closed Loop Biodynamics Vibration

Several incidents were encountered in which cockpit vibrations due to structure elastic modes fed back into the control stick through involuntary motions of the pilot's upper body and arm. The pilot comments were that it affected both control and comfort but no obvious safety affect, test point was aborted, rating was 7 and it must be improved. The pilot also emphasizes that it is not PIO, the test was low gain open loop test, and it was high frequency vibration.

This phenomenon is referred to biodynamic coupling[7], further engineering data analysis shown a resonant peak in the power spectrum of the pilot's stick inputs at a structural mode frequency.

This example shows that vibration affect both comfort and activities, with the rating scale the vibration level was determined soon after test with agreement between test crew and design engineer. With the rating and comments, managers made the decision of optimizing aircraft software to improve the vibration very soon.

5. Conclusion

The subjective rating scale translates generalized ill-define problem into a relatively well-defined problem. The test crews' feeling or comment are transferred into better information that can be used by management and design engineers with very low cost.

Further statistics analysis of subjective rating and objective vibration data may be studied to define relationship between subjective rating and objective data, and refine the design requirement.

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