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Analysis of In-Flight Vibration of a Single-Engine Propeller Aircraft

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Abstract Shipping companies are employing the use of all modes of transportation, including air transport, to decrease the costs and amount of time associated with delivering goods on time to the end user. Packaged products therefore are introduced to a variety of hazards while being transported. One way to evaluate a packaged product's ability to withstand these hazards is to perform laboratory simulated tests designed to replicate and reproduce field data results. Current industry standards employed for evaluating and testing shipments by aircraft are potentially too severe and can result in over testing and produce false results. A single-engine propeller aircraft was instrumented with a field data recorder and vibration data was collected and analyzed. By using the internal pressure sensor of the field data recorder, the vibration data could be separated based on ground and in-flight vibration. The results of this project showed the in-flight vibration intensity is much lower than what current industry standards have published. The resulting power spectral density (PSD) profile can be used to evaluate packages traveling in a small parcel environment where a single-engine propeller plane will be employed.
Keywords *Aircraft Vibration; Vibration Testing; Air Transport; PSD Profiles*

1. Introduction

Over the past twenty years there has been a steady rise in products being purchased through e-commerce and dotcom businesses. Consumers purchasing goods through these sectors often have the ability to select next day or overnight delivery of the goods with a guaranteed delivery time. One of the common modes of transportation for these types of delivery systems is via aircraft.

There are other reasons for the increasing importance of air transportation. For example, in recent years the use of logistics to manage a supply chain has increased due to companies needing to reduce the costs of tied-up capital investments [1]. The logistical way of thinking becomes more and more common, where companies aim to reduce the costs of tied-up capital. The time factor has become more important as faster transport combined with efficient material flow means excess supplies are reduced along with storage costs. Additionally, the increased competition demands manufacturers to be alert to market changes more quickly – which means being able to forecast the flow of goods properly [2].

The rise in air transportation has led to the need to understand and properly characterize this distribution channel. Packages are transported via multiple distribution channels to reach their specified destinations. Throughout the various distribution channels, the packaged products are subjected to three major categories of dynamic hazards: shock, vibration, and compression. While shock and compression hazards cannot be overlooked when designing packages or packaging materials, the basis of this research focuses on vibration, specifically aircraft vibration.

The intensity of vibration experienced by a packaged product depends on the type of transportation used. Different modes of transport will produce different vibration inputs to the packaged product system. The vibration environment on cargo aircraft is broadly classified into two sources; internal and external. The excitation frequencies are highly dependent on the type of aircraft (turbojet, turboprop, reciprocating engine, or helicopter); while the amplitudes depend more on the flight mode (takeoff, climb, cruise, and landing) [3]. The internal sources of vibration are the aircraft's engine and the means of transferring the power into thrust. The external sources of vibration are air turbulence, intermittent air pockets, and weather patterns.

Multiple types of aircraft are used to transport materials and packages throughout the world. Collectively, these types of aircraft can be summarized into two main categories – jet engine and turbo propeller (feeder aircraft). Some jet engine aircraft commonly used by the United Parcel Services (UPS) in transporting materials and packages are Boeing 757-200 Freighter and the DC8-70 Freighter [4]. While these larger aircrafts can transport thousands to millions of packages to major metropolitan cities, if the packaged products destination is not immediately served by a major airport or is remotely located, it may be introduced into a feeder aircraft network in order to aid in delivering the package on time [5].

The objective of this research is to capture and characterize in-flight aircraft vibration occurring during the shipment of packaged products to better understand this distribution channel. Air transportation is a highly used mode of transportation today due to the ability to conduct overnight and next day shipments. With the advent of more powerful and versatile data recorders, such as Lansmont's SAVER™ 9x30 (Lansmont Corp., Monterey, CA), this study aims to better characterize in-flight vibration data for a single-engine propeller aircraft. Utilizing the data recorder's internal pressure sensor, vibration data can be separated into ground data and air data, enabling the creation of separate power spectral density (PSD) profiles. These separate vibration profiles enable future research to be conducted in the air transport environment and aid in the optimization of package design.

2. Materials and Methods

2.1. Published Air Vibration PSD Profiles

Currently, two published air vibration test profiles are available for evaluating packaged products: one within the ASTM D 4169–09 "Standard Practice for Performance Testing of Shipping Containers" and the other is located in ISTA 4AB [6, 7]. Additionally, two profiles were developed from studies conducted by Amgen and Lansmont Corporation using an instrumented unit load device (ULD) inside the aircraft and at Clemson University using an instrumented Rockwell Twin

Engine aircraft [8, 9]. Figure 1 depicts the following four PSD profiles: ASTM D 4169–09 Air Assurance Level II, ISTA 4AB, the Amgen study, and the Rockwell study. All of the profiles depicted are different from each other, but there are similarities between the ISTA 4AB, Amgen, and Rockwell profiles when comparing the frequency domain signature. With this result, it was determined that more research of the air transportation environment was needed to better characterize each aircraft's profile.

Both the ISTA 4AB and Amgen studies were conducted with an instrumented package placed inside of the cargo area of the aircraft. The package in both instances was a ULD. Both studies measured the container's response to the vehicle vibration, not the input itself from the vehicle. Current data collection techniques for obtaining over-the-road vibration data for a truck require the attachment of a recorder to the floor of the vehicle, and the data collected from those recorders is used to drive a vibration table simulation [10]. The Rockwell Twin Engine turbo propeller study and the current Cessna 172 aircraft study differs from other published studies by measuring vibration input into the cargo area of a turbo propeller aircraft versus measuring a package's response to such vibration.

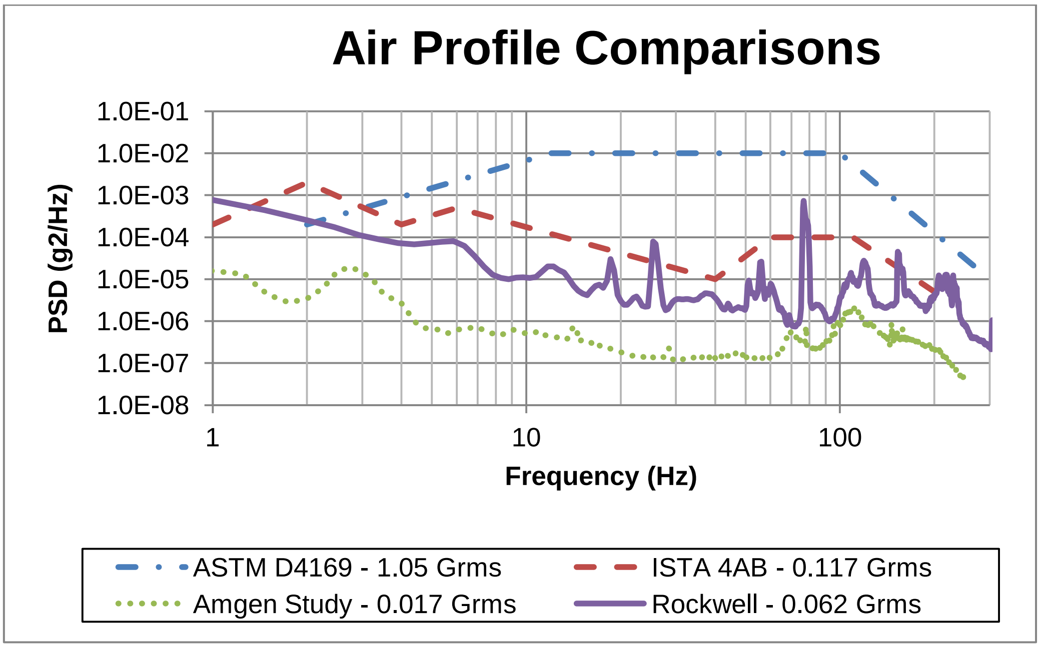

***Figure 1**: Comparison of Air Vibration Profiles*

2.2. Aircraft, Instrumentation and Recording Parameters

The aircraft instrumented for this project was a 1980 Cessna 172 Skyhawk (Figure 2). The engine has a single shaft with a cruising rotational speed of 2500 ± 5% RPM or 41.6 ± 5% Hz throughout the duration of all flights. Data was recorded using a field data recorder with an internal triaxial accelerometer mounted in an unpressurized cargo area, allowing internal atmospheric pressure gauge recordings of actual altitude during flight.

Figure 2: *Cessna 172 Skyhawk*

A Shock and Vibration Environment Recorder, (SAVER™), model 9x30 with SaverXware programming software was used in this study. This data recorder was selected due to the necessity of being able to record vibration and altitude in order to separate in-flight data from ground data.

The data recorder was rigidly mounted to the aircraft's cargo area using a custom aluminum fixture designed specifically for this application (Figure 3).

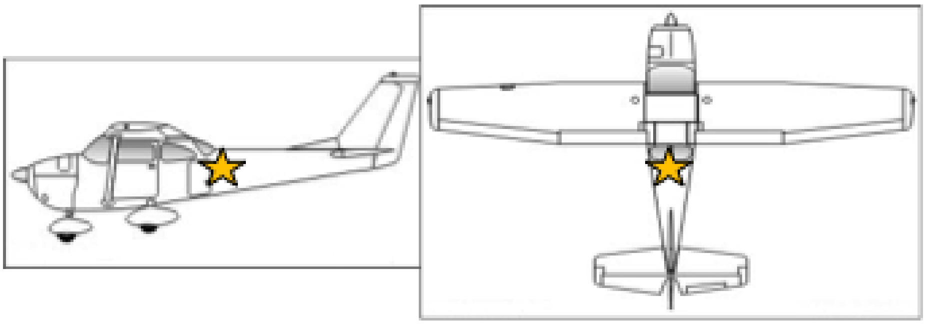

Figure 3: *Location of the Data Recorder (Represented by Star)*

The data recorder was programmed to record and analyze vibration using both signal and timer triggered data collecting methods. Signal triggered data refers to the data recorded during an event in which the intensity exceeds a preset threshold. Timer trigger data refers to the data recorder "waking up" at a preset frequency and recording for a preset duration. The following were the recording parameters used for this project:

- Signal Triggered Data
    - Event Trigger: Threshold: 0.50 G
    - Sample Rate: 1000 Samples/Sec
    - Record Time: 2.048 sec.
    - Signal Pre-Trigger: 20%

- Timer Triggered Data
    - Wakeup Interval: Every 30 sec.
    - Sample Rate: 1000 Samples/Sec
    - Record Time: 2.048 sec.

3. Results and Discussion

A total of 15 individual flights were recorded and analyzed for this project to provide the statistical validity needed to properly characterize the environment. The data was statistically analyzed and mean overall Grms levels were computed.

The flights recorded in this study varied in length from one to three hours. All of the flights were recorded in the Southeastern U.S., with the majority of the flights to destinations located in South Carolina. Some flights experienced the external excitation variables of air turbulence, air pockets, and/ or weather patterns. Interestingly, the internal excitations due to the propellers rotating at 41.6 ± 5% Hz are not visible in the aircraft vibration data (Figure 4). This was possibly due to vibration absorbers built into the engines that absorbed the energy produced at the operating frequency. Table 1 shows the average overall Grms values for the timer and signal trigger data recorded from the fifteen individual flights.

***Table 1:** Timer and Signal Trigger Results*

	Timer Trigger (g^2/Hz)	Signal Trigger (g^2/Hz)
Overall Grms	0.110	0.191
Standard Deviation	0.014	0.021

While the maximum accelerations recorded were as high as 1.83g, these levels represented discrete events occurring during takeoffs and landing; whereas the typical steady state vibration did not exceed 0.3g. Not all flights recorded during this study produced signal triggered data. This was due to the aircraft not experiencing any acceleration over 0.50 G during that particular flight.

Figure 4 represents the timer and signal triggered data showing the differences in intensity. Although the two PSD profiles have a similarly shaped curve, the intensity of the signal triggered data was greater than that of the timer triggered data. The average overall Grms level of the fifteen flights for the timer trigger data was 0.110, while the average overall Grms level of the fifteen flights was 0.191 for the signal trigger data.

Figures 5 and 6 display the averaged signal and timer triggered data overlaid with the published breakpoints from Rockwell Twin Engine turbo propeller study. These figures illustrate some of the similarities and differences in the shape of the curves for the data collected in this study with that of Rockwell Twin Engine turbo propeller study. These similarities indicate a similar frequency response of the aircraft measured in the two studies.

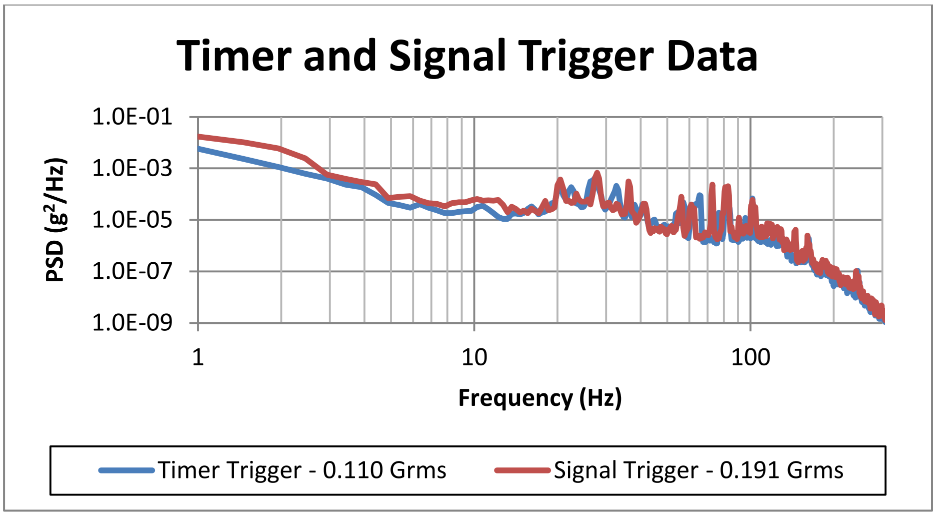

Figure 4: *PSD Profiles for Average Timer and Signal Trigger Data*

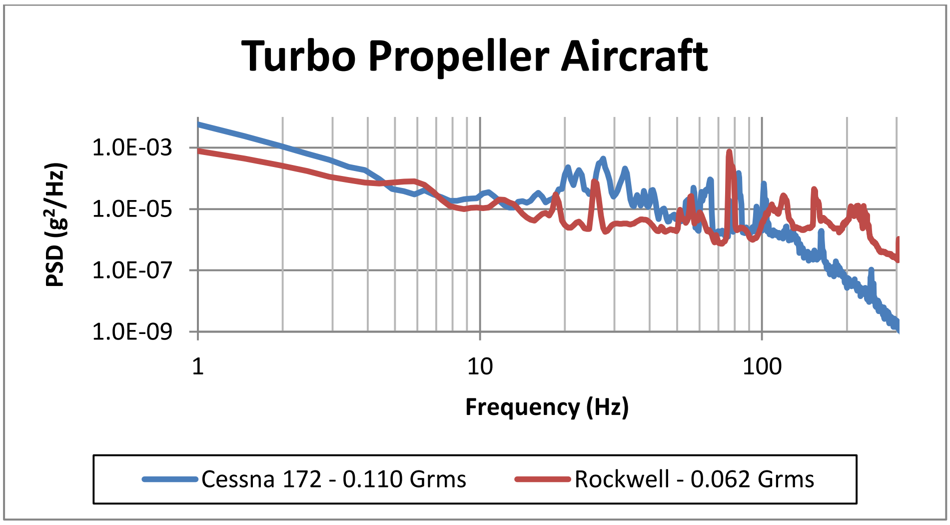

Figure 5: *Averaged Timer Trigger Data for the Cessna 172 and the Rockwell Twin Engine*

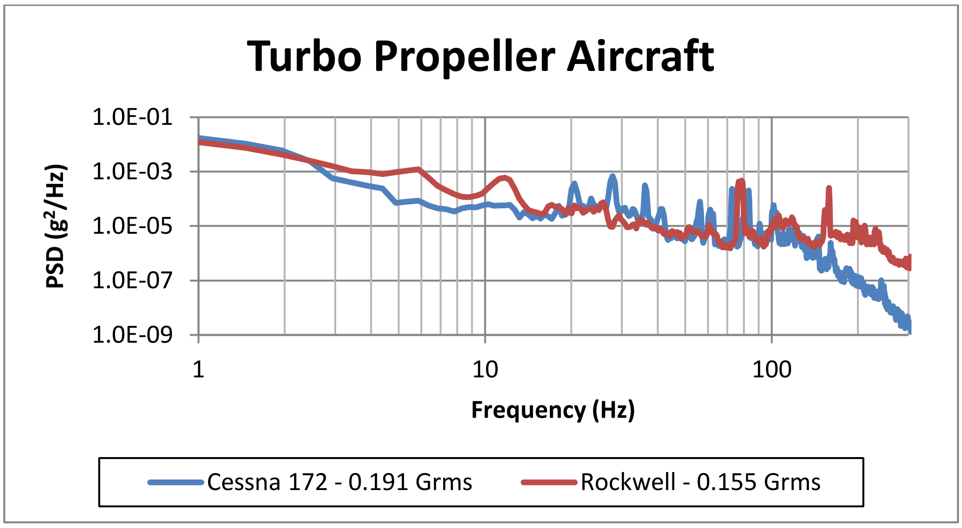

Figure 6: *Averaged Signal Trigger Data for the Cessna 172 and the Rockwell Twin Engine*

4. Conclusions

Recent technological advances in data recording have made it possible to record at a higher sample rate and separate segments of an aircraft's flight using pressure change. Being able to separate these segments makes it possible to individually characterize and analyze a particular aircraft's environment. The analyzed data from the environment and aircraft shows current test methods for aircraft vibration simulations exceed the actual environment for which the simulations are meant to represent. When data from previous studies were compared with that which was collected from this study, the results showed that the ASTM D 4169-09 Air PSD profile exceeds the actual vibration environment.

The maximum accelerations recorded occurred primarily during the ascent and descent of the aircraft. The maximum accelerations recorded were as high as 1.83g. These levels represented discrete events occurring during takeoffs and landings: whereas the typical steady state vibration did not exceed an intensity of 0.3g.

The excitation from the engines rotating at 41.6 ± 5% Hz was not visible on the PSD spectrums. This was believed to be due to vibration absorbers built into the engine producing a smoother, more comfortable ride for the passengers and cargo at typical operating engine speeds.

This method of collecting data could be used to understand the vibration in different aircraft in order to generate vehicle specific vibration profiles. By having multiple vibration profiles exhibiting the random vibrations experienced on an aircraft, the goal of a more optimized package and product system could be met.

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