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2aNS5. Characterizing nonlinearity in jet aircraft flyover data

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This paper examines evidence of nonlinear propagation in noise data collected during flyover measurements of three different military jet aircraft. The measure used to examine the waveform data for nonlinearity is the skewness of the time derivative of the pressure waveform during the maximum amplitude portion of the flyover. The derivative skewness has been used in the past to identify nonlinear steepening and shock formation, which causes large positive derivative values. A plot of the maximum 0.5 s equivalent level with the derivative skewness calculated from the 6 dB-down portion of the recorded waveforms shows a clear correlation between the two quantities for all three flyovers, irrespective of engine condition, altitude, or microphone location. Although the trends differ somewhat between the aircraft and the effects of propagation distance and merit further consideration, these preliminary results could point toward a simple model for establishing bounds on nonlinear propagation in flyover data.

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1. Introduction

The knowledgebase regarding the nonlinear propagation of military jet aircraft noise has grown in recent years. Studies involving full-scale engines and static aircraft have involved identifying these effects[1-4], the development of numerical schemes for far-field predictions[5-9], and examination of measures for near-field characterization[10]. However, analyses involving flyover data from military jets have been sparse, notable exceptions being those by McInerny *et al*. [11,12] McInerny and her coauthors built on her previous launch vehicle analyses[13] and examined military jet flyovers at a number of microphones along a line perpendicular to the flight track. For each flyover, they found the 0.5 s waveform segment containing the maximum pressure amplitude and then calculated the level and skewnesses for the pressure and its time derivative. They plotted the skewness values as a function of the maximum level and, irrespective of microphone location or aircraft condition, they found a clear correlation between maximum level and pressure derivative skewness increases. A much weaker correlation between pressure waveform skewness and level was found. Additional analyses[12] were performed to examine data trends as a function of microphone height for the statistical and other measures.

The skewness is the normalized third central moment of the probability density function; it is a measure of the distribution's asymmetry. The waveform steepening and shock formation that occur as part of nonlinear propagation result in an asymmetric distribution – large positive derivative values at the shocks yield positive skewness. Thus, the skewness of the pressure derivative can be an effective measure of acoustic shocks embedded in noise. Apart from the studies by McInerny *et al*.[11,12], the statistics of the time derivative have been analyzed for jet and rocket noise in a number of recent studies[10,14-18], including application to crackle[19,20]. To help provide quantitative insight, Shepherd *et al*.[21] and Muhlestein and Gee[22] have examined the derivative skewness characteristics for one-dimensional scenarios simpler than jet noise. This article builds upon the analysis by McInerny *et al*. by examining correlations between maximum level and the pressure and derivative skewnesses for three different military jet flyovers.

2. Measurements Summary

In this article, the three tactical aircraft and their associated field measurements are labeled 1-3, with Aircraft 1 corresponding to the same data set analyzed by McInerny *et al*.[11,12] In all three measurements, data were collected along a line perpendicular to the flight track, with the aircraft at different altitudes and engine conditions. During data collection, the aircraft was either in level flight or climbing, at constant engine power. For the different measurements, Type-1, 12.7 and 6.35 mm microphones were located at various locations along the measurement track, with maximum elevations of 13, 50, and 90 m, for tests 1-3, respectively. The nature of the analysis permits a comparative analysis between the three measurements, despite microphones having different locations, etc. For all measurements, data were collected at sampling rates of 96 kHz or greater.

As mentioned previously, data were analyzed based on the 0.5-s average overall sound pressure level, L_p. Once the maximum level, $L_{p,\mathrm{MAX}}$, was found, the analysis window was determined using the 6 dB down points on either side of this maximum. This waveform segment was used to determine the pressure and derivative skewness values. An example of the pressure waveform and corresponding maximum level region is shown in Figure 1.

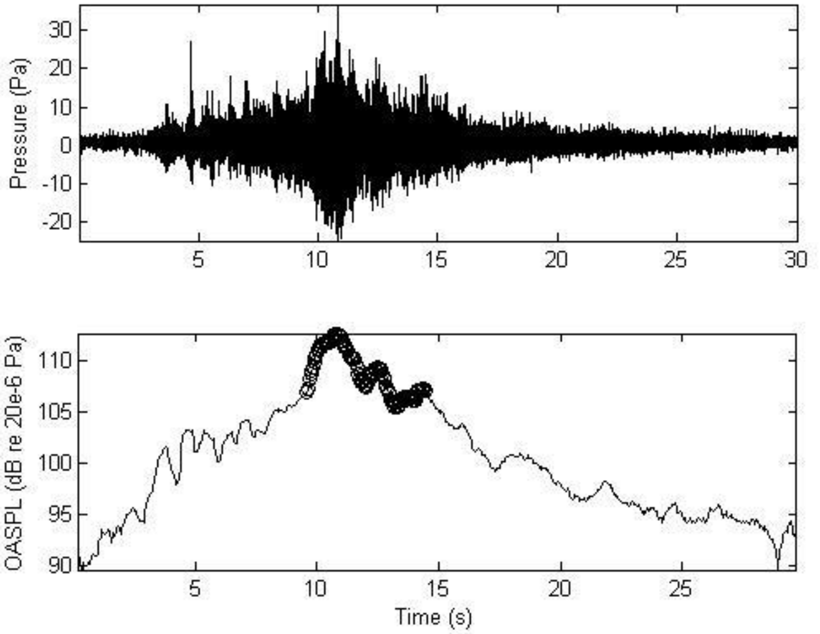


Figure 1. Example showing the pressure time history and the 0.5 s equivalent level (OASPL) as a function of time. The analysis window corresponding to the 6 dB down points on either side of the maximum level is denoted by the circles in the lower figure.

3. Analysis

Shown in Figure 2–Figure 4 are the skewness values from the maximum level segment plotted versus $L_{p,\mathrm{MAX}}$ for the three aircraft, respectively. The top plot in each shows the pressure skewness and the bottom plot corresponds to the derivative skewness. Aircraft 1 and 3 contain more detail regarding the flyover measurement points, as reflected in the corresponding legends. Examination of the three pressure skewness plots shows general agreement for Aircraft 1 and 2 – despite the scatter, there is a clear increase in pressure skewness with level. For example, a level of 120 dB re 20 μPa clearly corresponds to an average skewness of greater than 0.1. Different results are obtained for Aircraft 3, however.

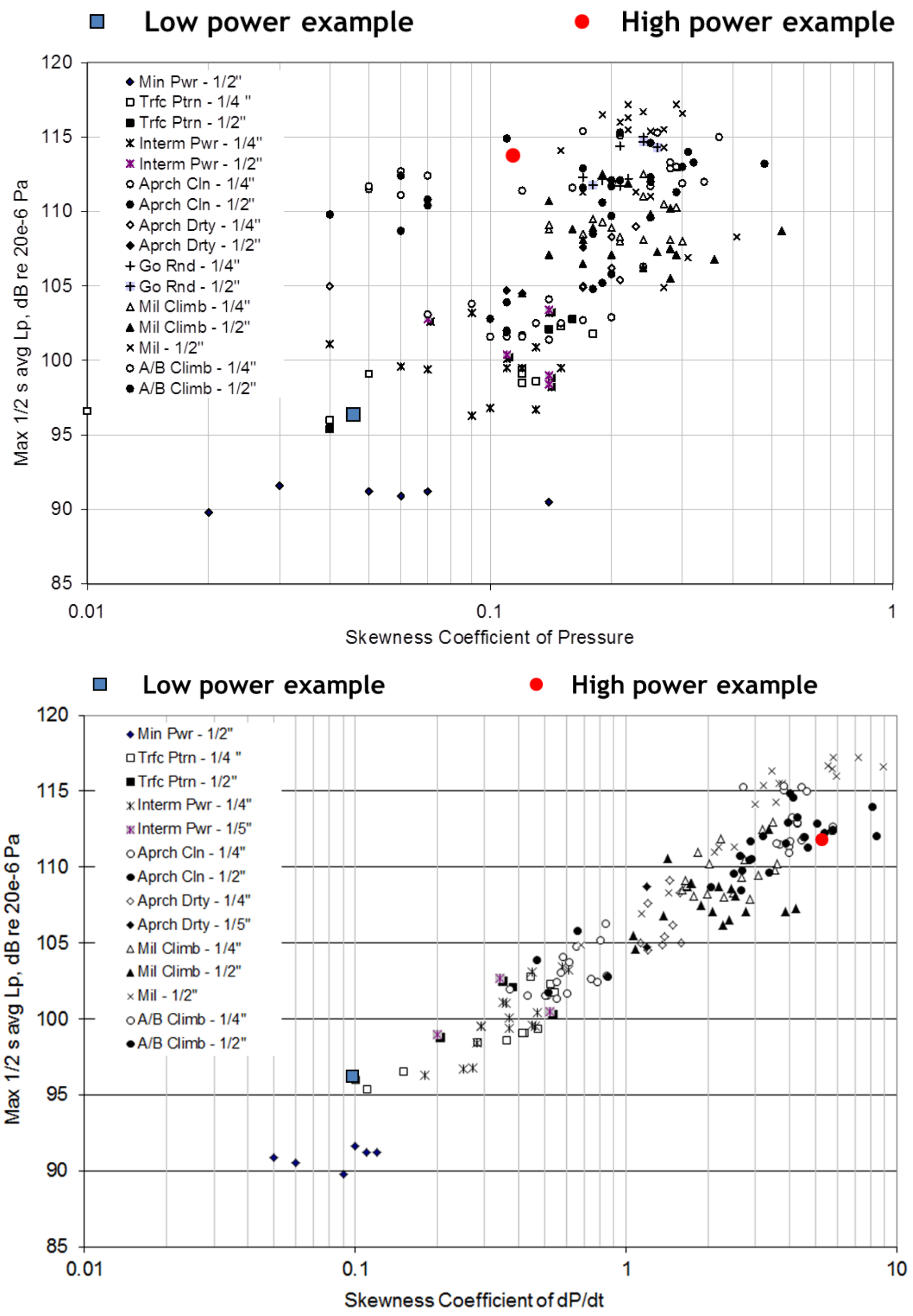


Figure 2. Pressure and derivative skewness as functions of $L_{p,\,\mathrm{MAX}}$ for Aircraft 1. The legend indicates engine condition and flight pattern, as well as the microphone size.

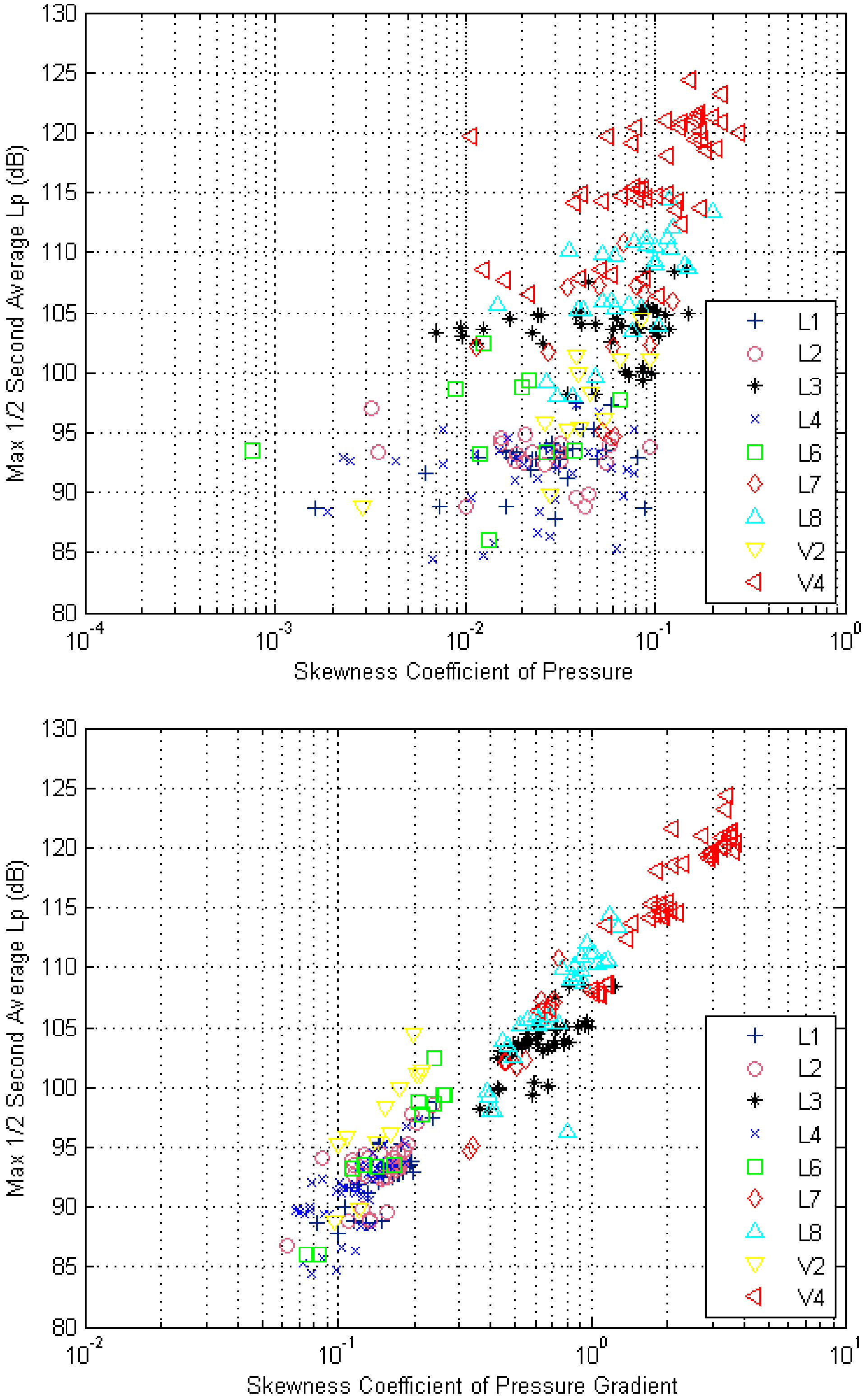
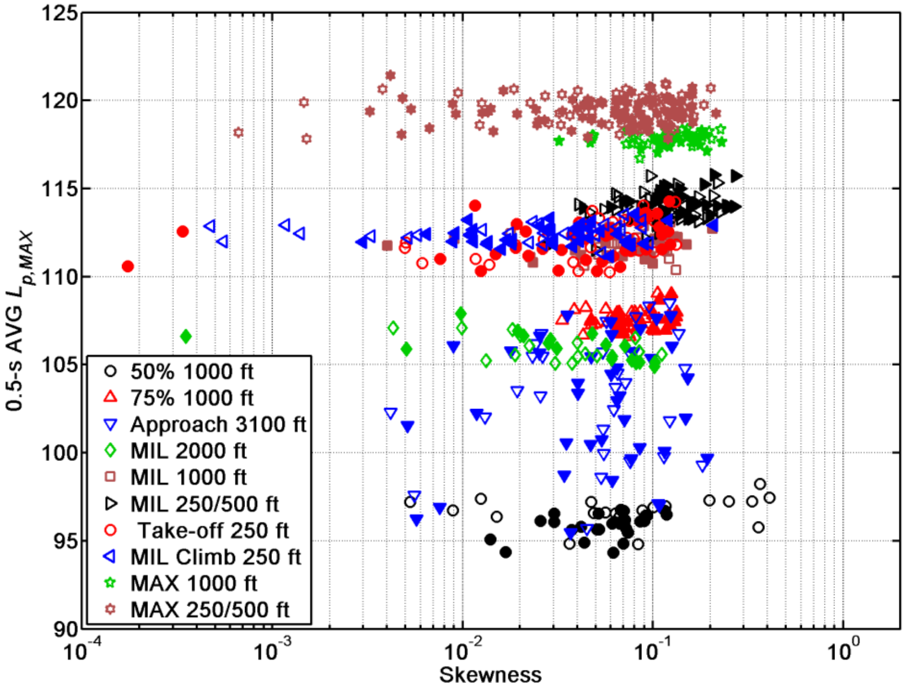


Figure 3. Pressure and derivative skewness as functions of $L_{p,\,\mathrm{MAX}}$ for Aircraft 2. The legend refers to different flyover test points.



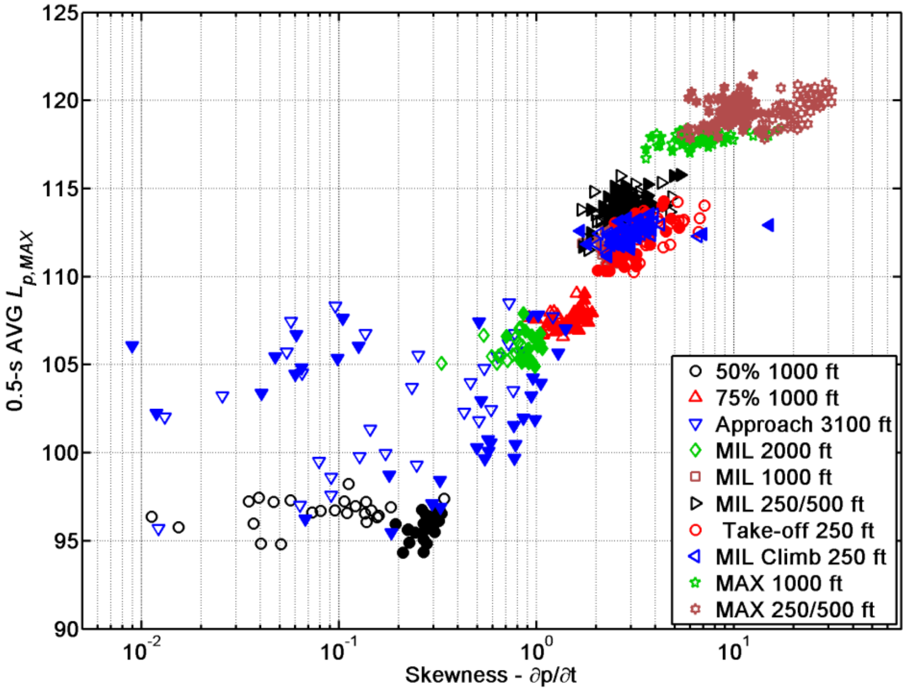


Figure 4. Pressure and derivative skewness as functions of $L_{p,\,\mathrm{MAX}}$ for Aircraft 3. The legend indicates engine condition and aircraft altitude. Open symbols denoted 6.35 mm microphones and solid symbols indicate 12.7 mm microphones.

For the pressure skewness from Aircraft 3, shown in Figure 4, there is significantly greater scatter for skewness as a function of level. Note that the open symbols refer to 6.35 mm microphones and the closed symbols refer to 12.7 mm microphones. For this test, the microphones analyzed were located on both sides of the flight path at a 305 m sideline distance and at different elevations. Consistency in aircraft setting for each flyover at a given test point (multiple flyovers are included for each condition) results in a relatively small variation in level at the microphones. This is true for all conditions except for the "Approach 3100 ft" for which there is a larger variation in $L_{p,\mathrm{MAX}}$. This could be due to the fact that it is a relatively low power condition at a high altitude. The large scatter in skewness for a given condition is presumably due to meteorological variation with altitude and from test to test, as there appears to be little systematic behavior when analyzing individual microphones. Correlation of pressure skewness scatter with weather conditions could be the subject of future analyses. There is a slight noticeable trend of average skewness increase with the highest engine powers, with the maximum reaching values of ~0.3 with the aircraft at maximum power. This is similar to the values seen for Aircraft 1 and 2.

The three derivative skewness plots in Figure 2–Figure 4 reveal a different trend. There is appreciably less scatter in the derivative skewness with level, which is somewhat remarkable. Whatever the cause for the greater variability in pressure skewness, level is the single greatest determining factor in the behavior of the derivative of the data. For Aircraft 3, there is one pass condition that does not fit the trend at low amplitudes – an Approach power with the aircraft at 3100 ft. It is possible that the higher altitude and meteorology led to a lower skewness for a given level. There also appears to be a flattening of the trend in Figure 4, corresponding to a large increase in derivative skewness with level for maximum power conditions. This would correspond to the presence of significant shocks in the waveform at distances greater than 300 m, which has been seen for the F-22A and the F-35AA in Refs. 7 and 9, respectively. Future analyses may involve other microphones from the test of Aircraft 3 that were closer to the flight path and would have been subjected to higher levels and could reveal what happens to the derivative skewness for greater $L_{p,\mathrm{MAX}}$. In any event, these skewness values in excess of 10 are consistent with shocks being present, according to previous studies by Shepherd *et al.*[21] and Muhlestein and Gee[22].

The derivative skewness plots from the three aircraft are compiled in Figure 5. Beginning at a skewness value of approximately 0.01, the increases in derivative skewness for Aircraft 1 and 3 nearly overlay each other, with an approximate 13 dB increase in level per decade for skewness. The skewness for Aircraft 2 increases more slowly with level; there is an approximate 20 dB level increase per decade for skewness. There are clearly other factors than overall sound level, such as characteristic frequency, that affect the derivative skewness and therefore the nonlinear content in a signal. However, the reasonable collapse for multiple aircraft suggests that the nature of the propagation is relatively insensitive to details in engine condition, provided that a similar level is produced.

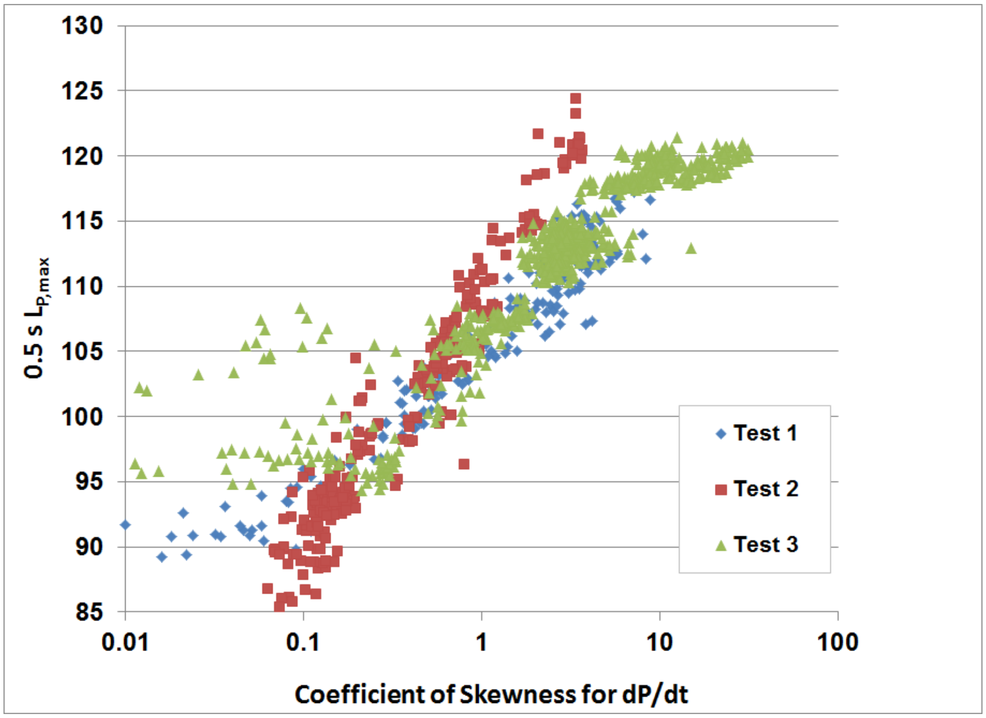


Figure 5. Compilation of the derivative skewness plots for all three aircraft (tests).

4. Conclusion

This study has corroborated the previous results of McInerny *et al.*[11], that the correlation between increases in level and derivative skewness are significantly greater than for the pressure skewness. In some sense, the results of this study are surprising. That data from three different aircraft, collected under different meteorological conditions, and involving different microphones, distances, and engine conditions, could yield similar behavior for derivative skewness as a function of maximum level seems astounding. Future analyses need to probe the details of the tests as a function of microphone type, height, distance, etc., but these results can guide those investigations. If a tie between derivative skewness and human perception of nonlinearly propagated noise can be found, then a model could be developed to connect engine condition to level and from level to nonlinear content. The “McInerny curves” in Figure 5 are an initial step in that direction.

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