ASSESSMENT OF CONTROLLABILITY OF MICRO AIR VEHICLES

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ABSTRACT

In the last several years, we have developed unique types of micro air vehicles that utilize flexible structures and extensible covering materials. These MAVs can be operated with maximum dimensions as small as 6 inches and carry reasonable payloads, such as video cameras and transmitters. We recently demonstrated the potential of these vehicles by winning the Fourth International Micro Air Vehicle Competition, held at Ft. Huachucha, Arizona in May 2000. The pilots report that these vehicles have unusually smooth flying characteristics and are relatively easy to fly, both in the standard RC mode and “through the camera” when at greater distances. In comparison, they find that similar sized vehicles with more conventional rigid construction require much more input from the pilot just to maintain control. To make these subjective observations more quantitative, we have devised a system that can conveniently record a complete history of all the RC transmitter stick movements during a flight. Post-flight processing of the stick movement data allows for direct comparisons between different types of MAVs when flown by the same pilot, and also comparisons between pilots. Eventually, practical micro air vehicles will be autonomously controlled, but we feel that the smoothest flying and easiest to fly embodiments will also be the most successful in the long run. Comparisons between several types of micro air vehicles will be presented, along with interpretations of the data.

BIOGRAPHY

David Jenkins and Peter Ifju are Associate Engineer and Associate Professor, respectively, at the Aerospace Engineering, Mechanics and Engineering Science Department at the University of Florida in Gainesville, Florida, USA. Mujahid Abdulrahim is an undergraduate student in the same department. Scott Olipra is an undergraduate student in the Computer and Information Sciences Department at the University of Florida.

INTRODUCTION

At the University of Florida Department of Aerospace Engineering, Mechanics and Engineering Science, we have been actively designing, building and test flying micro air vehicles over the last four years. During this time, we have also competed each year in the International Micro Air Vehicle competition, a mission-based contest that we have won for the last two years. For more details about this annual competition see the website at **http://aeroweb.aero.ufl.edu/microav/Main.htm**. Largely by the process of trial and error, we have developed a unique type of micro air vehicle shape and structure which incorporates flexible carbon fiber wings with extensible membrane coverings. Using this unusual approach, we have been able to fly remotely piloted aircraft as small as 4-½ inches maximum dimension, an example of which is shown in Figure 1. These vehicles are made with a carbon fiber framework covered with a clear polymer film and have wings covered with a thin, latex rubber membrane. For a complete description of our fabrication methods, see Ifju et al (1).

Pilot reports and video recording through a small on-board camera indicate that these vehicles have unusually smooth flying characteristics, both during visual contact flying in the conventional RC mode at close range and also when flying more remotely using the transmitted video from the on-board camera. We consider the smooth flying qualities to be an important characteristic of practical micro air vehicles in the future, even when they will be made to fly autonomously. In the continuing design process we are striving to make the feedback information concerning handling qualities more objective and quantitative, rather than relying solely on the pilot's informal comments. Although using verbal feedback has been successful so far, our ability to evaluate the effects of design changes is limited and often inconclusive. To address this shortcoming, we have developed a system for recording the pilot's control inputs during the entire flight and we are developing tools for objective interpretation of this data. The purpose of the study described in this paper is to evaluate a number of alternate methods of presentation of control input data in order to select the ones with the best sensitivity to flying qualities of the vehicles. Measurement and analysis of flight control inputs using these methods would then be used to develop quantitative objective functions in the design optimization process.

RECORDING OF CONTROL INPUT DATA

Most of our test flying is done using conventional RC equipment at close range, keeping the vehicle in continuous visual contact. Because of the small size of the vehicles, flying at distances greater than about 100 feet can quickly cause loss of orientation unless the pilot is flying by monitoring the video output from an on-board camera. The RC transmitter produces a radio frequency signal that causes the RC receiver carried in the vehicle to develop a series of pulses of varying pulsewidths (pulse width modulated or PWM) which are delivered to the control surface servos as the command signals for the desired positions of these surfaces. On the equipment we use, the pulses are generated at a constant frequency of 40 Hz. To capture this control input information, we have developed a simple system which uses a second RC receiver on the same RC frequency as the flight unit to monitor the pulse widths of the servo signals on the various servo terminals on the receiver (see Figure 2). We use a Motorola MC68HC11 microcontroller connected to a notebook PC via an RS-232 serial connection at 9600 bps. The HC11 decodes the PWM signal by comparing the pulse width of the incoming signal against its own internal clock. Each servo pulse width is sampled as a 16 bit number and converted into a hexadecimal string. This string is converted to a four-character ASCII string, which is sent to the PC. The data are stored as text files, which can be later processed by a spreadsheet program. With this system, stick input data is recorded without any contact or interference with the pilot or the micro air vehicle and the recording can be done at any reasonable range within the operating range of the RC system (at least 1100 meters).

ANALYSIS OF STICK INPUT DATA

Various approaches to the analysis of the stick input data were tried in an attempt to find a suitable metric that would correlate well with the pilot's comments concerning the handling qualities during a particular test flight. The following methods were considered and evaluated on four sets of flight test data:

- application of descriptive statistics to the data, specifically the standard deviation
- histograms of stick positions during the flight
- counting the number of stick motion reversals during a given time period
- autospectra of stick position during the flight
- autospectra of stick movement rate during the flight

Our expectation was that some of these methods would exhibit some obvious features related to the pilot's workload during the flight, and thus serve as useful tools for evaluating flying qualities.

FLIGHT TESTS

One of the issues of special importance to us is the noticeable difference in flying qualities between our extensible membrane wings and more conventional rigid wings. We have observed that the flexible wings offer smoother flights and easier flying qualities. Therefore, we have included in our test series flights with both flexible wings and rigid wings, all using the same fuselage. To make for an obvious situation with poor flying qualities, the center of gravity for the vehicle was moved to the rear of the optimum position by about ½ inch by rearranging internal components on one series of flights. Finally, to show the effects of difficult flying conditions, one set of flights was made on a day with strong and gusty winds. For all the tests, we used a 10-inch maximum dimension vehicle with a 0.01 cubic inch internal combustion engine, similar in shape to the vehicle shown in Figure 1. The same pilot made all the flights.

For the sake of brevity, only four selected flights are analyzed and reported here. "Case 1: Flexible wing forward CG" refers to a 10-inch size vehicle with the balance point set to produce reasonably good flying characteristics. "Case 4: Flexible wing forward CG gusty" refers to the same set up but tested on a particularly gusty day. The other flights were all done within a one-hour period on a day with strong but fairly steady winds. The test identified as "Case 2: Flexible wing aft CG" refers to the ½ inch aft CG configuration that leads to pitch instability and requires an obvious increase in the pilot's workload. "Case 3: Rigid wing forward CG" indicates that a rigid wing of the same planform, camber and thickness was substituted for the flexible wing. This wing was made using the same framework of carbon fiber members as the flexible wing, but with a single layer of cured, woven carbon fiber cloth substituted for the flexible membrane. The weight of each configuration was kept the same.

Our vehicles are equipped with elevon flight control surfaces that use one servo operating each movable surface. The RC transmitter provides the necessary mixing functions so that the pilot moves the control stick in the usual way during flight, as if there were ailerons and an elevator. To separate out elevator inputs from roll inputs, it is only necessary to add or subtract the two servo command signals recorded during the flight. All flights begin with a hand launch into the wind, and the pilot flies a racetrack pattern approximately 100 feet long (into the wind and downwind) and 50 feet wide (crosswind). The typical flight lasts for two to four minutes.

Stick input data for a typical flight is shown in Figure 3. Full scale stick deflection is equivalent to about 1250 counts on the scale shown, although this number depends on the amount of trim applied to the RC transmitter by the pilot. For some of the analysis options, it was necessary to differentiate the stick position signal. Figure 3 also shows the first time derivative of the stick position data, achieved by subtracting consecutive data values.

FLIGHT TEST RESULTS

For consistency and use within the numerical analysis functions of a Quattro Pro spreadsheet program, representative sets of 512 continuous data points were selected from each flight test. All of the results that follow were derived from the same sets of data points.

Descriptive Statistics: The population standard deviation provides a convenient measure of the tendency for the stick position to vary from some mean value. Table 1 shows the standard deviation values for both elevator and roll inputs for the four test cases. The vehicle with the best handling qualities also exhibits the smallest values for the standard deviation, both in the elevator input and the lateral stick motion, or roll input. Less encouraging is the observation that on the gusty day the same machine produces numbers as large as or larger than the two configurations observed to be more difficult to fly. A surprising result is the appearance of very large values for the rigid wing aircraft, which the pilots report flies better than the aft CG flexible wing configuration, though not as well as the forward CG configuration. The scale of the numbers corresponds to the 1250 count full stick displacement mentioned previously.

Histograms of Stick Position: Figure 4 shows histograms of elevator and roll input stick positions. The vertical scale is the relative number of times out of 512 that the stick position falls within a particular bin (bins are 10 counts wide). These charts display some of the same type of information provided by the standard deviation values, albeit in a more visual way. Especially for the elevator inputs, vehicle configurations with poor handling qualities exhibit broadened position distributions as expected. The roll input distributions are less clear, with only minor broadening of the shapes. The mean value of these roll input distributions could be interpreted as the preferred trim value which in some cases is not centered on the stick neutral position. Because of the nature of dynamic roll input movements, a symmetrical shape is expected and is observed here. Elevator inputs would be expected to have a somewhat bimodal shape, because of the need for slight up elevator during turns and neutral elevator during straight and level flight. Each of the curves presented does show some tendency toward the development of two broad peaks.

Counting Reversals of Stick Motion: The differentiated data was examined for changes in sign during the 512 data period, which covers 12.8 seconds of flight time. These changes in sign of the derivative are interpreted as changes in the direction of motion of the control stick. Note that this does not mean changes from "up" elevator to "down" elevator, for example, but rather changes from "moving toward up" to "moving toward down". The total number of sign changes for each control input for each of the four flight tests is shown in Table 2. Surprisingly, the numbers for elevator changes are all quite similar for all tests as are the numbers for roll input changes, which are about twice as high. The best flying configuration leads to the largest numbers, instead of the opposite, which was anticipated. These numbers apparently have more to do with pilot's reaction time and tendencies than with characteristics of the aircraft.

Autospectra of Stick Positions: By utilizing the Fast Fourier Transform feature of the spreadsheet program, power frequency spectra were generated for elevator and roll input positions for the four flight tests and are presented below as Figure 5. The y scale used was arbitrarily selected, but remains the same from test to test. These spectra were observed to fall off rapidly with increasing frequency, and so the horizontal scales were expanded to provide a view of the lower frequency components. Following the example of Padfield et al (2), the premise can be made that intensity or power at each frequency is related to the pilot's workload. Further, two primary components of the workload can be identified, one related to the maneuvering of the aircraft and the other to the stabilization of the vehicle. Maneuver related workload is expected to dominate the lower frequency range (slow, planned stick movements), while stabilization is expected to involve higher frequency "corrective" motions of the controls. Examination of the spectra produced could certainly lead one to believe that pilot workload at .5 Hz and below is abundantly present and could be mainly due to the maneuvering task itself. For example, in windy conditions such as were present during our tests, turns must sometimes be made at intervals of only 2 to 4 seconds. Presumably, at all times during the flight, a series of smaller, faster control inputs are required to stabilize the vehicle. These may present themselves as the higher frequency components that appear in the spectra. If this is the case, then some differences in stabilization workload are evident from test to test, with the best flying configuration showing appropriately the least workload at higher frequencies. This effect is most prominent in the elevator results, but also manifests itself somewhat in the roll input results, consistent with pilot reports.

Autospectra of Stick Movement Rates: Another view, as presented by Jones et al (3), is that by transforming the stick position data by a suitable "whitening" process a more uniform power spectrum can be developed which provides a better view of the different pilot workload activities. One such transformation is differentiation of the data with respect to time so that movements of the controls instead of positions are analyzed. The differentiated data was analyzed as before and the spectra are presented as Figure 6. Information now appears over a wider frequency range as expected. Looking first at the elevator rate data, it can be seen that obvious differences develop between the vehicle with the good handling qualities and the other configurations (aft CG and Rigid wing), even in the presence of gusty wind conditions. Important differences appear throughout the whole frequency range presented, but most convincingly between 1 and 10 Hz. The lack of power above 10 Hz is probably a natural consequence of the pilot's minimum reaction time (about 0.1 second). The roll input rate spectra show similar tendencies.

DISCUSSION AND CONCLUSIONS

The method of recording control stick input during flight clearly provides data that has potential for providing some insight into comparative flight vehicle handling qualities. Of the methods of data analysis examined, the most effective seems to be spectral analysis of control input movement rates. At least as far as the four test cases are concerned, forming autospectra of differentiated stick position data provides a convenient yardstick by which flying qualities of micro air vehicles can be objectively evaluated and compared. As far as the pilot is concerned, his extra "workload" beyond simple maneuvering is unquestionably related to how often he must make rapid (in the range 1 to 10 Hz) stick movements to maintain stability during the flight. The spectral analysis method also reveals tendencies of the pilot, an aspect that we have not explored so far. The wavelet analysis approach, described by Jones et al (3), may also offer some new insights and views of the data and we plan to evaluate this method. Some of the other methods examined may also find applications in our program, such as the use of the histogram or the simple statistical mean to quickly determine appropriate trim changes after the first flight of a new configuration. The pilot is often unable to tell how much trim may be required, even after a flight is completed. This method of recording and analysis could also be easily extended to recreational RC flying, perhaps being of use to the competitive flyers for “fine-tuning” their skills or student pilots to learn to fly more “smoothly”. We plan to use measurements of this type to help guide us in making appropriate design changes to our future micro air vehicles.

REFERENCES

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2. Padfield, G. D., Charlton, M. T., Jones, J. P., Howell, S. E., & Bradley, R., Where does the workload go when pilots attack maneuvers? An analysis of results from flying qualities theory and experiment, Twentieth European Rotorcraft Forum, Amsterdam, October 1994

3. Jones, J. G., Padfield, G. D. & Charlton, M. T., Wavelet analysis of pilot workload in helicopter low-level flying tasks, The Aeronautical Journal, p. 55, September 1999.

		Standard Deviation of Elevator Input	Standard Deviation of Roll Input
Case 1:	Flexible Wing forward CG	**228.3**	**193.6**
Case 2:	Flexible Wing aft CG	**314.4**	**211.3**
Case 3:	Rigid Wing forward CG	**456.8**	**272.4**
Case 4:	Flexible Wing fwd CG gusty	**377.7**	**245.5**

Table 1. Standard deviation of the stick position for elevator and roll inputs.

		Number of Reversals of Elevator Input Stick Motion	Number of Reversals of Roll Input Stick Motion
Case 1:	Flexible Wing forward CG	**91**	**164**
Case 2:	Flexible Wing aft CG	**89**	**140**
Case 3:	Rigid Wing forward CG	**76**	**164**
Case 4:	Flexible Wing fwd CG gusty	**81**	**155**

Table 2. Stick motion reversals in 512 data recorded at 40 Hz, over 12.8 seconds.

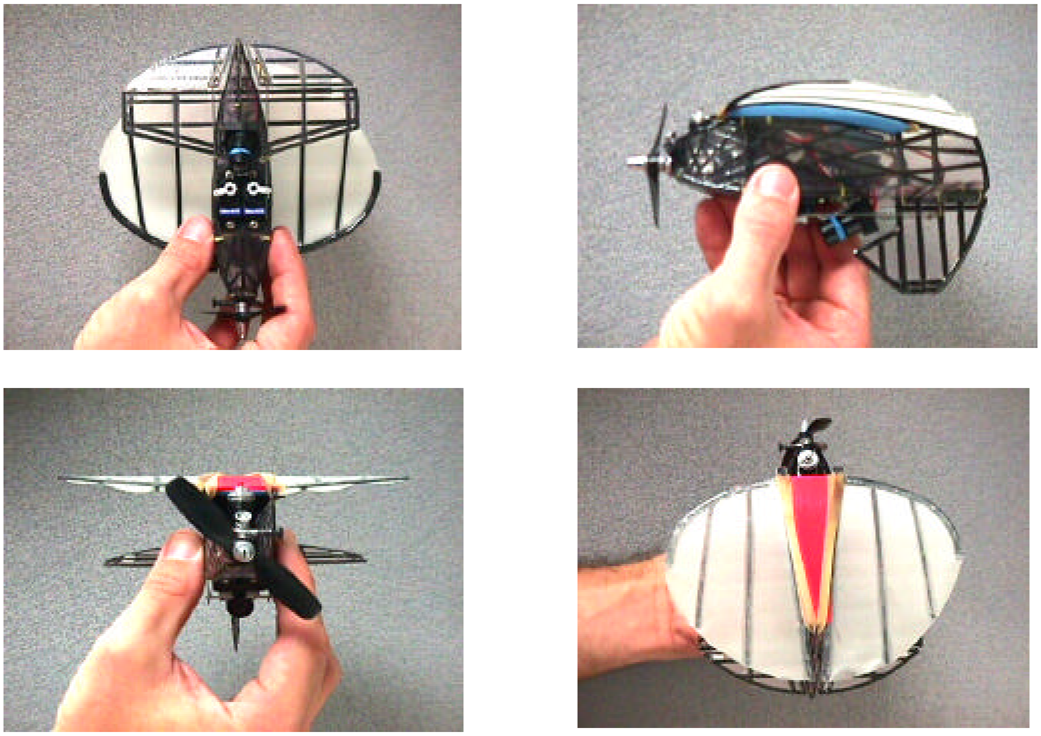

Figure 1. Type of micro air vehicle used in this study. This example is 6 inches maximum dimension and is powered by a 0.01 cu in internal combustion engine.

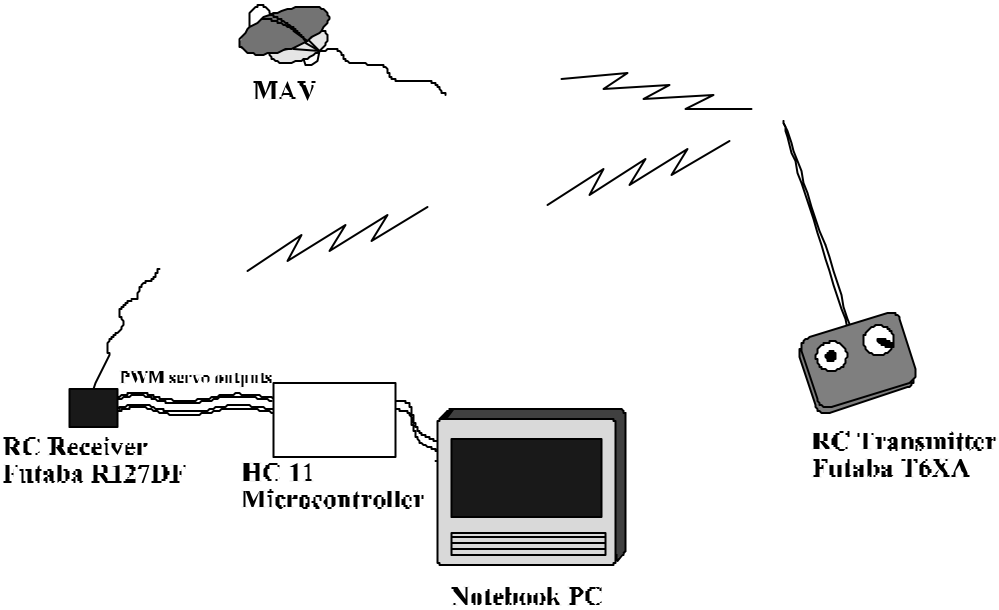

Figure 2. Flight control input data recording system.

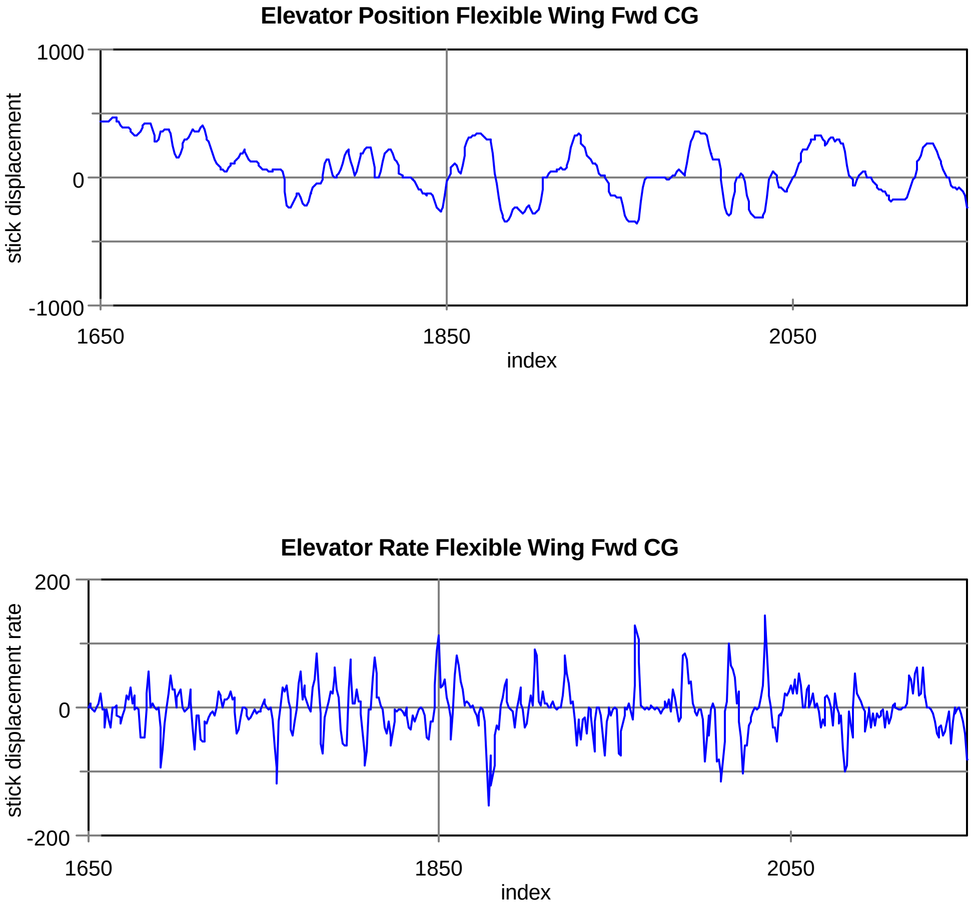

Figure 3. Example of elevator input data from typical test (above). Below is the same signal after differentiation (units are counts in 1/40 second).

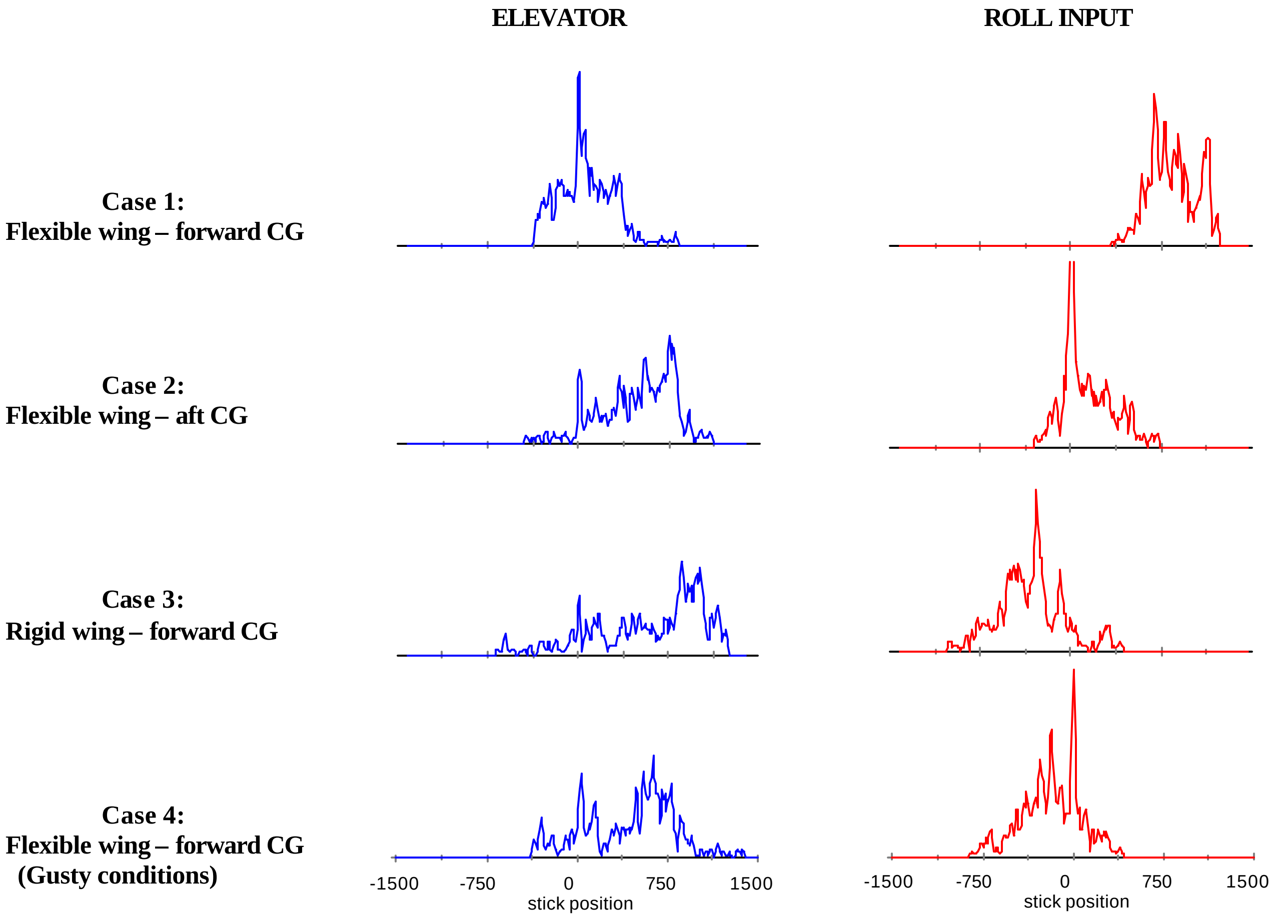

Figure 4. Histograms of elevator position and roll input position. The ordinate is the relative frequency of occurrence for each stick position. The differing horizontal locations of the distributions reflect vehicle out-of-trim conditions.

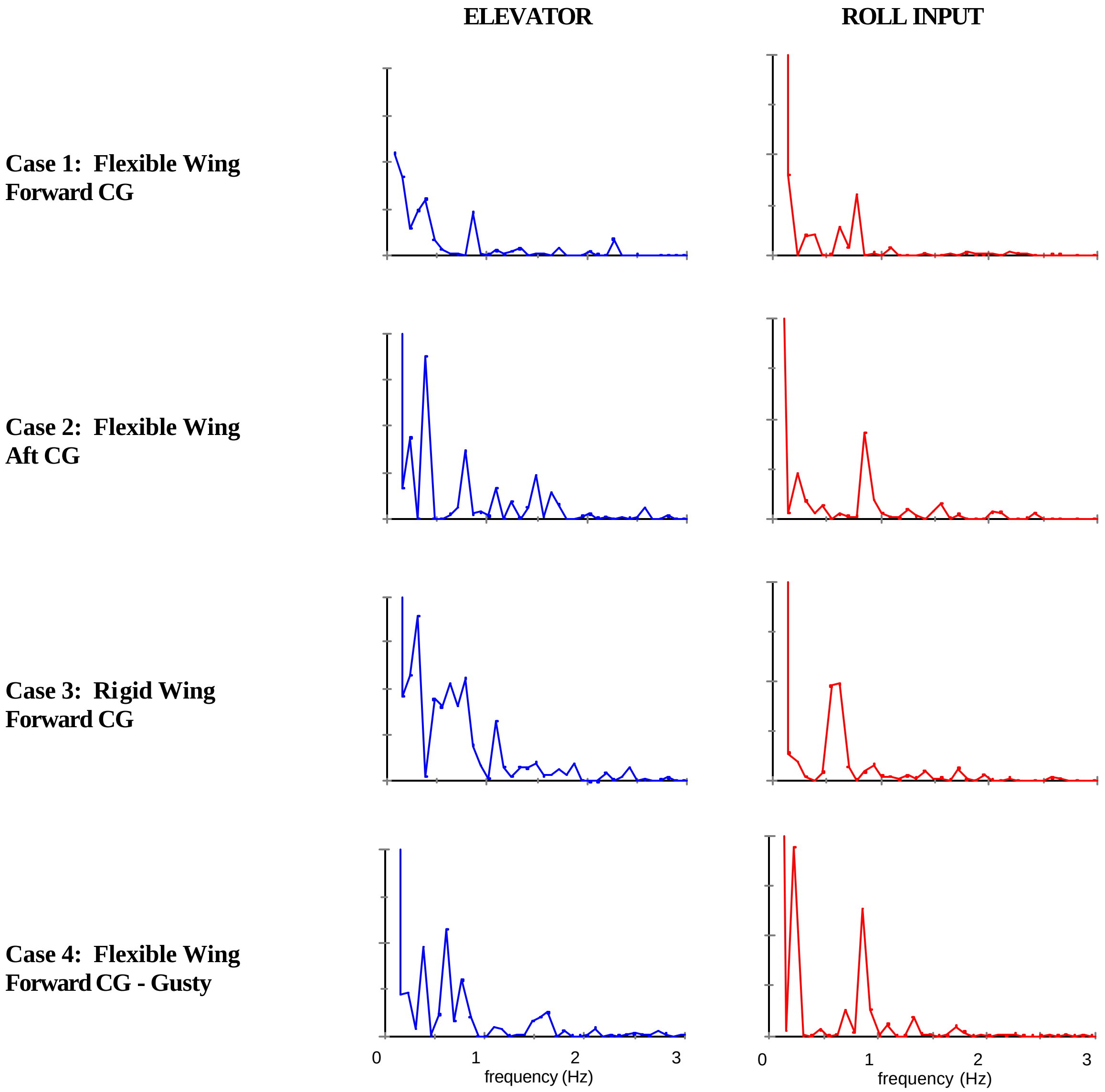

Figure 5. Autospectra for elevator input position data and roll input position data. The vertical axis in each case is the square of the amplitude of the Fast Fourier Transform, or the relative power at each frequency in the spectrum. 512 data points were processed in each case.

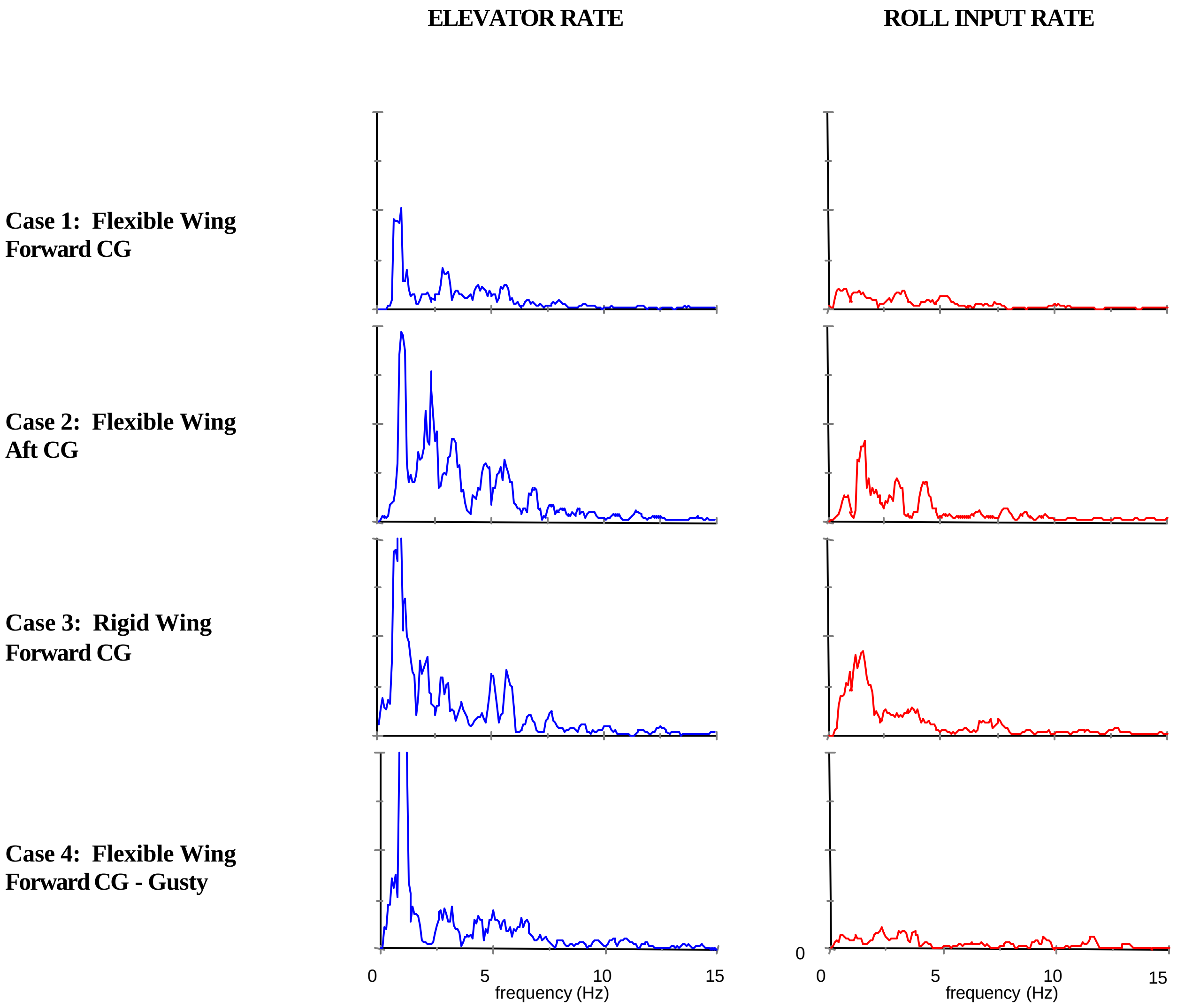

Figure 6. Autospectra of elevator movement rate data and roll input rate data. The vertical axis is the relative power at each frequency. The curves were generated by processing the differentiated elevator and roll input data. 512 data points were processed in each case.