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Paper Session III-B - Ultrasonic Correlation Bolt Tension Analyzer

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ULTRASONIC CORRELATION BOLT TENSION ANALYZER

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Abstract

We describe our efforts in the development of an improved ultrasonic bolt tension analyzer (bolt gage) for use in precision tensioning of bolts in critical applications. This new instrument uses correlation techniques to ameliorate the peak jumping problems usually associated with ultrasonic bolt gages. Our instrument has been put through substantial (though not exhaustive) tests, with very good results.

Background and Introduction

Ultrasonic Bolt Gages have been used with good success for at least twenty years to measure the tension in critical bolts. Most of these instruments use the "standard" time-of-flight (sonar) technique to measure bolt stretch, from which the tension is derived by Hooke's law. When the instrument works, it works well: with temperature compensation and careful technique, errors of the order of one percent of the total measurement can be obtained. However, when the instrument has an occasional error, it is of the order of tens of percent, and it is difficult to detect when an error occurs. Our experiences in the Space Program tell us that for any degree of reliability in the measurements with an ultrasonic bolt gage, it is necessary to use a very skilled operator with an oscilloscope to monitor (continuously) the perormance of the instrument, and occasionally correct the stated output to the correct output. Several groups (KSC, Raymond Engineering Inc., and Langley Research Center, among others) over the years have tried to improve the reliability of the ultrasonic bolt gage, with limited success. The reliability is improved, but at a cost in accuracy, or in not being able to remove and replace the transducer, or in the complication of the system which adds new failure modes to be kept track of by the skilled operator. What the program has wanted has always been the "red light/green light" box that any mechanical technician can use to tension a bolt with absolute accuracy. The technician just puts the wrench on the bolt and twists it until the light turns green. Such an instrument may never happen, but the old time-of-flight ultrasonic bolt gage can be greatly improved. The remainder of this paper describes the problems with, and our efforts to improve the bolt gage, primarily by using all the information in the ultrasonic echo waveform, rather than just some particular tiny feature of the echo.

Ultrasonic Bolt Gagery

Here is the problem: one needs to attain a certain tension in some bolt; for example, one that holds the lid on a nuclear reactor or holds the orbiter to the external tank, and that tension needs to be accurately known, say to within a few percent. If one uses a torque wrench, the accuracy is about +/-20 percent, which is inadequate. If one uses strain gages (internal or external to the bolt) one must put up with a lot of electronics, tweakery, and the basic magic associated with strain gage measurements. In some instances, it is possible to measure the actual physical stretch of the bolts, but this is a delicate mechanical measurement (generally about 0.0001 inch accuracy) to attempt in the gritty and inacessible real world.
The solution that first appeared maybe 30 years ago is the use of ultrasonics to measure the bolt tension. The longitudinal sound mode in particular has a speed that decreases with material tension, which makes it easy to use. (One just backs out the fraction of the apparent change in length due to the tension. This can be done because the tension increase and the actual stretch increase in time-of-flight do not compete, but add.) The instruments work on the basis of accurately measuring (or tracking by means of an ingenious phaselock loop) the time-of-flight of a sonic pulse, down to about a nanosecond for most bolts. The instruments that have appeared to do this share a common trait, namely, when they work, they work well (errors on the order of a percent), but when they don't work (and give you errors of ten or twenty percent) they don't give any indication that they aren't. The new problem is not accuracy, but performance reliability.

The performance of the ultrasonic bolt gage really depends on how well the instrument can keep track of the return waveform, since this wave form suffers distortion (both attenuation and "interference" shape changes) when the bolt is stretched. Consider the usual way a bolt gage tracks the location in time of a return pulse: after a delay from the pulse's being sent, a comparator waits for the return signal to exceed some set threshold. Wben the comparator trips, a trap is set for the next negative-going zero crossing. When that zero occurs, the nanosecond clock is stopped and the time-of-flight of the pulse is defined, as shown in Fig.1.

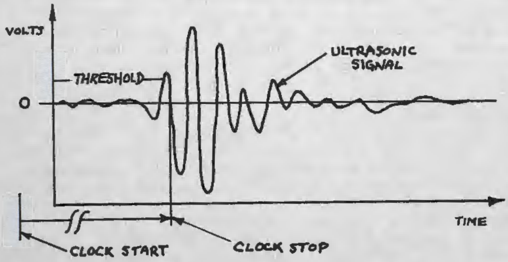

Figure 1. Feature Location for Time-of-Flight Determination

If the pulse is sufficiently attenuated, or if the first peak disappears or a new first peak appears due to interference effects as the bolt is tensioned, then a corresponding error will be generated by this circuitry's mis-identification of the first peak.

There have been two basic approaches to the solution of this "peak-jumping" problem. The first (Gleman and Hallberg actually built such an instrument) is to detect the peak jump by the stuttering of the clock at a jump, and to continuously monitor the output of the gage as the bolt is tensioned. A "strip chart" continuous time record of the tension will show any jumps and whether their magnitude needs to be added or subtracted to obtain the true reading. The second is to try to use the entire return waveform information, and not just some tiny and unreliable feature of the waveform, to calculate the time of flight. NASA Langley (Allison) did this by using a pulsed phaselock loop, measuring a frequency shift to determine the bolt tension. NASA Kennedy has done this by brute force waveform correlation, as described in the present work.

Correlation Bolt Gagery, Experiments Therein, and Results Thereof

We used two basic techniques. In the first, we sent out a pulse and recorded the return waveforms from some arbitrary time zero related in a repeatable fashion to the instant the pulse was sent. These waveforms can be compared for the case of the tensioned and the slack bolt. The technique for comparison was simply to integrate the product of the two waveforms as a function of the delay introduced into the slack waveform. The time of flight is then defined as that time delay for which the integral is maximized. The second technique uses only one waveform, but both the first and second echoes. Here we time shift the first return and correlate it with the second return as a matched filter. The advantage here is that the arbitrary zero time is removed; thus, it is no longer possible to introduce a "calibration error" into a measurement by having a holdoff potentiometer be adjusted or drift occur between measurements. For the purposes of the present work, we will call the first method, "first return correlation", and the second method, "first-second return correlation". Both methods worked well. Experimental setup is shown in Fig. 2, and sample data are shown in Fig. 3.

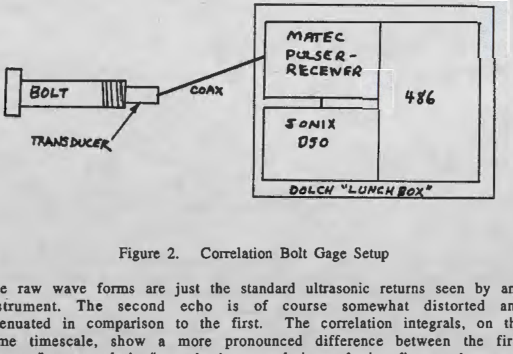

Figure 2. Correlation Bolt Gage Setup

The raw wave forms are just the standard ultrasonic returns seen by any instrument. The second echo is of course somewhat distorted and attenuated in comparison to the first. The correlation integrals, on the same timescale, show a more pronounced difference between the first return "autocorrelation", and the correlation of the first and second returns.

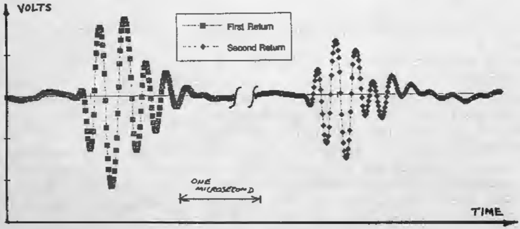

Figure 3A. Ultrasonic waveforms

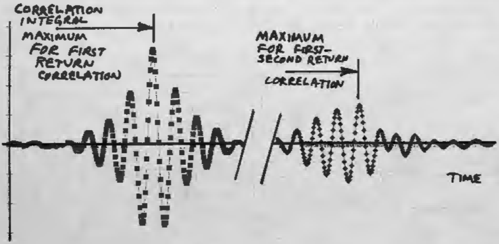

Figure 3B. Correlations

We calculated the correlation integrals using smoothed (running 5-point Lagrange interpolation) waveform data, since our data was taken at ten nanosecond intervals and we needed one nanosecond intervals. (This does not really add any information to the waveforms or to the integrals, but it makes the data look smoother and makes casual observers feel better.)
We performed many laboratory and field tests of the correlation bolt gage, usually side-by-side with other ultrasonic bolt gages. These tests cannot be characterized as exhaustive, but they were extensive enough to include

situations in which other instruments "jumped peak" (giving erroneous results) while the correlation gage, hooked up to the same (untouched) transducer and bolt gave a reliable and accurate measurement.
A comparison of the performance of both correlation techniques with two Raymond Engineering time-of-flight gages (the PDX-934 and the Bolt Gage II) for a particular data run on particular bolt is shown in Fig. 4.

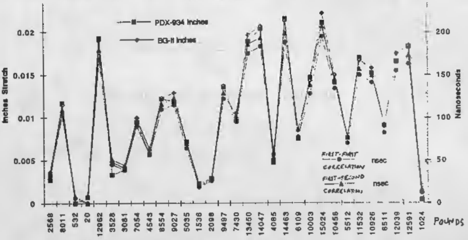

Figure 4. Comparison of Various Bolt Gages

In this figure, the axis of abscissas appears scrambled, because it is: we took the data in random order, so that time-systematic errors would be apparent. If all the gages were equal and accurate, then any particular bolt load would result in only one value for the ordinate. It is obvious that this is not the case, but it is also obvious that the correlation methods work as well as the standard gages. Note that the outputs of the Raymond gages are given in inches of stretch, while our correlation gage outputs nanoseconds of timeshift. Either can be converted to pounds of tension in the bolt.

Conclusions and Recommendations

This correlation technique provides a viable and apparently reliable bolt gage. In particular, the first-second return correlation seems essentially immune to the peak jumping problem that plagues the other techniques and causes unreliable measurements.
More exhaustive tests, incuding extensive field tests of the correlation gage side-by-side with all other versions of bolt gage, need to be undertaken. The data obtained should be used to develop reliability models for all versions of the ultrasonic bolt gage. The aim will be to determine the most reliable version for critical appplications.
Assuming that the correlation gage will win this contest, a "production prototype" should be developed for technology transfer to industry.