AN ULTRASONIC TECHNIQUE FOR
AXIAL BOLT-STRESS DETERMINATION*

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INTRODUCTION

In this paper we describe an automated technique for measuring bolt axial stress and report stress measurements made using the technique in our laboratory. We propose to use this technique in an instrument with which the quality control engineer will be able to check bolt preload on assembled machines. The instrument will allow measurement to be made with access to only one end of the bolt and will not require either prior knowledge of the original bolt length or disturbance of the bolted joint.

The need for such an instrument can be demonstrated by noting that the desired preload on a threaded fastener, such as a bolt, is usually achieved during assembly by application of a specified torque. The empirical relationship [1]

$$F = Q / (0.2 \times D) , \quad (1)$$

where F is the load on the fastener, Q is the applied torque, and D is the diameter of the fastener, relates the torque to the tensile force applied to the bolt. If no friction were present in the threads or under the head of the bolt, then the force would be given by

$$F = (2.0 \times Q) / (D \times \tan p) , \quad (2)$$

where p is the angular pitch of the threads. For a one inch diameter bolt with 8 threads per inch, Eq.(2) reduces to

$$F = Q / (0.02 \times D) , \quad (3)$$

which is different from Eq.(1) by a factor of 10. From this theoretical argument we conclude that about 90% of the torque applied to the bolt is

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used to overcome frictional forces. Small fluctuations in these frictional forces, for a given fixed applied torque, will therefore result in large fluctuations in the preload applied to the bolt.

Blake and Kurtz [2] measured a variation from 90% to 95% in the fraction of the applied torque required to overcome friction in ten 1/2 inch bolts all preloaded with 67 lb ft of applied torque. The useful preload, as determined from bolt elongation, varied by almost a factor of two in these experiments. Heyman [3] also investigated the reliability of torque as a measure of preload. He observed preload fluctuations as large as 70% for repeated application of the same torque.

Because of this large uncertainty in bolt preload when torque is used as a measure, an independent and more accurate determination of bolt stress can be expected to yield large improvements in machine reliability. Several techniques have been suggested for this purpose [3-5] and commercial ultrasonic strain monitors have been developed utilizing these and other methods. We have recently investigated a method of determining stress in bolts [6] which is different from previous ones in that it is capable of determining stress after the bolt is in place and it requires no independent information about the present or unstressed length of the bolt. Moreover, using this method, one can determine bolt stress with access to only one end of the bolt.

Our approach to determining stress requires two ultrasonic measurements on the installed bolt: the flight times for shear and longitudinal waves propagated down the axis of the bolt and reflected from the far end. We have shown that these two measurements can be used to calculate the present length of the bolt and the applied axial stress provided that the bolt material is sufficiently well-characterized [6]. An approach similar to ours, though not quite so detailed, was suggested by Williams et al [7] in their review of ultrasonic stress measuring techniques. They propose calculating the axial stress averaged over the length of the bolt from the ratio of flight times for shear and longitudinal waves.

The goal of our work is to develop an automated instrument capable of determining stress with the single application of a transducer to one end of the bolt. Toward this end, we have automated the process of stress measurement in our laboratory utilizing a microprocessor to control the measurement process and to reduce the data. In this paper we describe the experimental setup for the automated measurements and report the results of experiments using the setup.

In our automated setup measurement is made by application of a transducer unit containing both longitudinal and transverse elements. The microprocessor controlling the measurement selects each element in succession and subsequently calculates the applied stress.

THEORY

The theory for our measurements is given elsewhere [6], so we will simply indicate the starting point and results here for completeness. We follow the familiar approach of Hughes and Kelly [8] to obtain the equations

$$\rho v_l^2 = \lambda + 2\mu - D_l T \quad (4)$$

and

$$\rho V_2^2 = \mu - D_2 T, \quad (5)$$

where ρ is the density, λ and μ are the Lamé constants, T is the tensile stress, V_i are the longitudinal and shear sound speeds, and the D_i are combinations of the second and third order elastic constants given in [8]. In words, Eqs.(4) and (5) simply remark that, to a good approximation, the moduli depend linearly on applied stress.

In order to account for the unstressed portions of the bolt in an approximate way, we suppose the flight path is comprised of two parts, one stressed and one unstressed. The flight times are then given by

$$t_i = 2 \left[\frac{a}{V_i} + \frac{\kappa}{V_{i0}} \right], \quad (6)$$

where t_i are the flight times, a is the length of the stressed part of the bolt, κ is the length of the unstressed part of the bolt, and the subscript o indicates the value in the unstressed state. The values of the subscript i are 1 for the longitudinal case and 2 for shear.

Equations (4) through (6) yield the stress equation

$$T = \frac{t_1 V_{10} - t_2 V_{20}}{t_1 V_{10} d_1 - t_2 V_{20} d_2 - 2\kappa(d_1 - d_2)} \quad (7)$$

where

$$d_1 = \frac{D_1}{2(\lambda + 2\mu)}, \quad d_2 = \frac{D_2}{2\mu}. \quad (8)$$

We suppose that the approximate value of κ is known for a particular application. If the application is such that it is only a small fraction of the total bolt length, then it may be set to zero in Eq.(7) with no significant loss of accuracy.

Equation (7) gives applied stress in terms of material properties, the measured flight times, and the geometric parameter κ .

EXPERIMENTAL SETUP

In order to determine stress our apparatus needs to select each of the transducer elements in succession, measure the corresponding time-of-flight, and then calculate stress from the results of the measurements using Eq.(7). A schematic diagram of the apparatus is shown in Fig. 1.

Selection of the desired transducer element is accomplished by means of a relay controlled by the output from a standard digital-to-analog (D/A) converter module in the computer.

To begin our time-of-flight measurement we excite the transducer element, whose center frequency is about 5 MHz, with a short (about 0.1 microsecond) square pulse. The input pulse and the response to successive echoes from the far end of the bolt are recorded at 50 nanosecond intervals and the information is stored in a RAM buffer for later access by the CPU.

Fig. 1. Diagram of the apparatus used to make automated stress measurements. The numbers in circles indicate the order in which successive operations take place. The dashed line represents the computer enclosure.

For the purpose of acoustic signal recording we designed and built a fast converter board capable of analog to digital conversion at rates up to 20 million samples/sec. Because the computer operates with a 5 or 8 MHz clock and therefore cannot accept the data as fast as it is converted, we included 32 kbytes of RAM on the converter board and hard-wired a converted data bus directly into this RAM. This allows the computer to access the converted data at its leisure. Our approach closely parallels that of Hull et al [9], who used a digital oscilloscope and cross-correlation methods to measure sound velocity. A significant difference is that memory limitations within the scope forced them to use a sequence of measurements with carefully timed delays in order to record successive echos. In our case the entire record is converted and stored.

Once the data is stored we need to accurately determine the time between successive echoes, i.e. the time-of-flight. We can accomplish this by determining numerically the time shift necessary to cause each echo to accurately coincide with its successor. For this purpose we borrowed a concept from pattern recognition theory; that of a cost function, which is in this case a generalization of the area between an echo and its shifted neighbor. The cost function we used is

$$f(q) = \int |s(t) - s(t + q)|^n dt \quad (9)$$

where $s(t)$ is the recorded signal as a function of time, q is a variable shift, n is a parameter which changes the sensitivity of the function, and the integral is over the duration of the echo. Time-of-flight is taken to be the value of q that minimizes $f(q)$. In Fig. 2. we show three successive echoes shifted to coincide with one another using this scheme.

As a check of our method we requested that the National Bureau of Standards perform time-of-flight measurements on steel samples which we furnished them. These measurements were obtained through the courtesy of Dr. Gerald Blessing. The samples were two inch diameter pucks, machined and polished to 1" and 1.5" thicknesses. They were not lapped, and so were not sufficiently uniform dimensionally to fully enjoy the accuracy available from NBS. Even so, machining on the samples was sufficiently precise to fulfill our requirements. The NBS results are compared to our automated results in Table 1.

The reported uncertainties in the NBS measurements were less than 2 nanoseconds. We believe the uncertainty in our measurements to be around 10 nanoseconds.

Fig. 2. Three successive echoes shifted using the cost function given by Eq.(9). The solid line is the first echo, the dashed line is the second, and the dotted line is the third.

Table 1. Comparison of Automated Time-of-Flight Measurements With Standard Measurements from NBS

Sample	t_1 (μ sec)		t_2 (μ sec)	
	NBS	JAG	NBS	JAG
1"	8.303	8.307	15.196	15.195
1.5"	12.672	12.652	23.192	23.185

In order to apply a known tension to the specimen bolts we mounted them in a tensioning device described elsewhere [6]. Briefly, it consists of a vertically mounted double-acting center pull jack, a chamber for holding the bolt, and a hydraulic system for supplying a known, fixed hydraulic pressure to the jack rams. Since the ram area is known, we can calculate the load applied to the bolt. The head of the bolt protrudes above the sample chamber for access with the transducer. We have performed experiments in which a given load is approached from above and then below in order to establish that the friction in the jack is negligible for our purposes.

EXPERIMENTAL RESULTS

Before bolt stress could be measured it was necessary to empirically determine values for the material constants which appear in Eq. 7. To establish values for D_1 and D_2 , sample bolts were subjected to several predetermined stress levels and the corresponding shear and longitudinal times-of-flight recorded. V_{10} and V_{20} , the zero stress sound velocities, were determined by measuring times-of-flight in bolt sections surface ground and cut to exact length.

Results of these experiments have been previously reported [6] and are summarized in Table 2. It should be noted that values of κ are specific to our application and depend on how deeply the bolt is turned into the threaded hole or nut.

With the material parameters defined, the shear and longitudinal times-of-flight in a bolt may be measured and the bolt's state of stress calculated. In Table 3 we give the results of a series of automated stress

Table 2. Material Parameters Used to Calculate Stress from Time-of-Flight Measurements

Grade	Bolt Diameter (cm)	D_1	D_2	V_1 (cm/ μ sec)	V_2	κ (cm)
5	2.23	8.88	.40	.5905	.3230	1.25
	1.91	9.53	.46	.5912	.3222	1.00
8	2.23	8.67	.33	.5894	.3222	1.25
	1.91	9.53	.44	.5905	.3224	1.00

Table 3. Automated Stress Measurements on a 7/8" x 4"
Grade 8 Bolt

Applied Stress (MPa)	Calculated Stress (from ultrasonics) (MPa)	Time-of-Flight	
		Shear (μ sec)	Long. (μ sec)
0	30	68.68	37.51
130	130	68.70	37.58
260	270	68.71	37.64
520	480	68.79	37.79
610	550	68.92	37.89
0	60	68.67	37.52

measurements on a 7/8 inch by 4 inch grade 8 steel bolt. These results are typical of those obtained on a variety of 7/8 and 3/4 inch bolts ranging in length from 3 to 6 inches.

In practice, the axial loading in bolts comes about as a result of their being twisted into place and consequently bolts in place are normally in a state other than that of pure uniaxial stress. To facilitate the testing of our method on torqued bolts, a jig was constructed which allowed strain gages to be attached to, and readings made on, bolts tensioned by means of a torque wrench. This jig allowed the performance of a number of experiments producing results of the type shown in Table 4. The first set of measurements was performed with the bolt in a jack and pure axial tension applied. The second set was performed with the bolt in the jig, torqued to the indicated values. Equation (1) was used to calculate stress from the known applied torque. The results appear to indicate that applying stress via torsion has no significant detrimental effect on the accuracy of our technique.

Bolts in service are often coated with paint as part of the overall effort to inhibit corrosion in an assembly. To investigate the extent to which a layer of paint might affect our system of measurement, we measured stress in a bolt, first in its unpainted condition and then again after three coats of rust resistive paint had been applied to its head. The results of this experiment appear in Table 5. While measured times-of-flight increased slightly, as might be expected, the presence of paint does not appear to have interfered with the stress measurement process.

The uncertainties in stress calculated from our automated ultrasonic measurements may be seen to be about 60 MPa. At stress levels typical in machine design applications, say on the order of 400 MPa, this is an uncertainty of about 15%. This compares favorably with the relatively large uncertainties, discussed above, that one experiences when preloading the bolt to a specified torque.

CONCLUDING REMARKS

In conclusion, it appears that our apparatus for making automated stress measurements will serve as a suitable basis for developing a portable ultrasonic instrument for measuring stress. We expect the method to be useful in applications where the bolt design preloads are in the 250-400 MPa range. Variability of the material constants from one specimen to the next precludes reliable measurements below 100 MPa at present.

Table 4. Ram-Loaded and Torque-Applied Stress Measurements on a 7/8" x 4", Grade 8 Bolt

1. Bolt under Ram loading					
T ₁ (μ sec)	T ₂ (μ sec)	Applied Stress Calculated From Ram Pressure (MPa)	Stress From Strain Gage (MPa)	Ultrasonic Stress Measurement (MPa)	
37.66	68.56	618	623	624	
37.58	68.51	464	491	481	
37.48	68.45	309	326	290	
37.38	68.39	155	167	112	
37.28	68.32	0	1	-69	
2. Bolt under torque loading					
T ₁ (μ sec)	T ₂ (μ sec)	Torque (lb ft)	Stress From Strain Gage (MPa)	Ultrasonic Stress Measurements (MPa)	Stress From Torque Equat. (MPa)
37.35	68.37	100	151	65	79
37.42	68.40	200	240	195	157
37.47	68.42	300	333	304	235
37.49	68.44	400	389	341	314

Table 5. Ultrasonic Stress Measurements on a Painted and Unpainted Bolt

RAM Pressure (PSI)	Stress From Ram (MPa)	Unpainted		Painted	
		Measured Stress (MPa)	% Error	Measured Stress (MPa)	% Error
2800	618	648	5	589	5
2100	463	499	8	455	2
1400	309	356	15	327	6
700	154	212	38	205	33
0	0	-9		5	

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