

An Advanced Torque Auditing Method

The Magic of M-Alpha

By Jeff Drumheller



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The Magic of M-Alpha

A simple audit by turning a previously tightened fastener another few degrees and looking at the peak torque is not sufficient to determine if the fastener is tightened enough to achieve the desired clamping force.

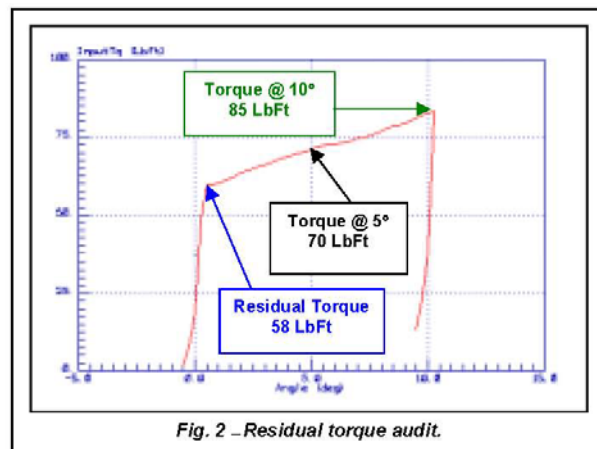
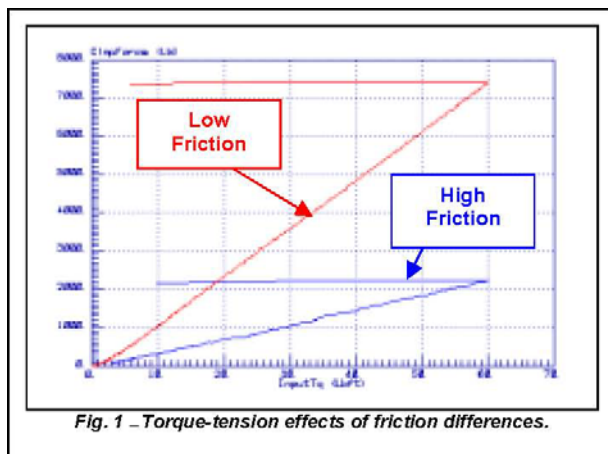
Millions of threaded fasteners are used each year to assemble products ranging from hand-held electronic devices to cars and trucks to heavy-duty earthmovers. As part of their quality control efforts, manufacturers have searched for the best way to effectively measure how well the assembly was put together. Since some sort of hand or power tool applies torque to the fastener, the easiest and most popular means of assembly verification is to measure the torque either dynamically during assembly or statically after the fact. Although these methods may be useful for many non-critical assemblies, a more complete method is needed for auditing critical joints where the clamping force holding the joint together must be of a sufficient amount to hold the assembly together. This complete method must somehow be able to determine, or at least estimate, the clamp load to ensure that the assembly is adequately tightened.

Auditing the Bolted Joint

The most common method for auditing a bolted joint has been to perform what is called a residual torque audit on the assembled part. This process consists of an operator advancing the previously tightened fastener 5° to 10° in the tightening direction and then observing the peak torque. The acceptability of the joint tightness is then determined by comparing the peak torque from the audit reading to the installation torque value. Often, this method accomplishes little more than to verify the performance of the tool that was used for the original tightening. This method may often reveal very little or no information regarding the clamping force that is holding the assembly together, which is the true aim of joint analysis. In addition, this type of torque audit can be very dependent upon the knowledge and influence of the operator conducting the audit.

If the friction coefficients, joint stiffness and installation process associated with a given bolted joint are uniform and repeatable, monitoring torque can prove to be an acceptable method of auditing. However, torque audits alone do not provide sufficient information to determine the clamp load attained in the joint. Torque data by itself can only verify the amount of work done on the joint, that is, if the required amount of torque has been applied.

Variation in friction coefficients can dramatically affect the integrity of a joint at a specified torque value. Understanding that the installation torque has to overcome both the underhead and thread friction before clamp load is achieved, any increase in either of the coefficients will increase the percentage of the installation torque needed to overcome the friction, leaving less torque available to produce tension in the joint. In other words, the more friction present in the joint the less clamp load that will be attained at a specific torque value. This can be seen in Figure 1 where two fasteners with different friction characteristics were tightened to 60 lb-ft (81 N-m) and the corresponding tension values were measured, Figure 1.



Residual torque values are very dependent upon the performance of the operator in conducting the audit. Large variations in torque values can result if the operator advances the fastener too far or not far enough. In addition, the peak torque reading of the audit is measured rather than the actual residual torque as shown in Figure 2.

Torque auditing can be successful if performed on noncritical joints that feature low scatter in both friction characteristics and installation torque. On more critical joints and those with high scatter in the installation process, more information is needed from the audit to verify joint performance. These types of joints require that the auditor ensure that the proper preload has been established.

M-Alpha Auditing Methods

In order to determine or better estimate the essential clamping force in a bolted joint, a new method has been developed that uses the recording and analysis of torque-angle signatures to determine the integrity of the joint. This method, called M-Alpha (M for torque or moment, Alpha for angle), can let the auditor monitor both residual torque and tension values in the joint as well as remove the user-dependent variable from the auditing process. The M-Alpha auditing method uses torque-angle signature analysis on residual torque audits to determine joint integrity.

Since the M-Alpha diagram was developed as an extension of *SR1*, a bolted joint design and analysis software package based on the German standard *VDI 2230*, the terminology remains true to the VDI standard terminology (M for torque, from the German term DrehMoment and alpha for angle).

The M-Alpha auditing method presents the tightening torque as a function of the bolt assembly angle, which correlates the stretch of the bolt to the angular displacement of the fastener. This relationship provides a method of monitoring the tension in the joint, or the bolt stretch, by analyzing the torque-angle signature of the audit.

Understanding the amount of tension in the joint allows the auditor to determine if the specified installation torque and tightening process provides the clamp load necessary to handle the working loads. Along with determining the joint integrity, the exact residual torque value can be determined by analyzing the torque-angle signature in addition to the peak torque values.

The M-Alpha diagram is the straight-line projection of the tangent to the torque-angle assembly curve as projected backwards from the final elastic tightening point to the zero or prevailing torque level, as shown in Figure 3.

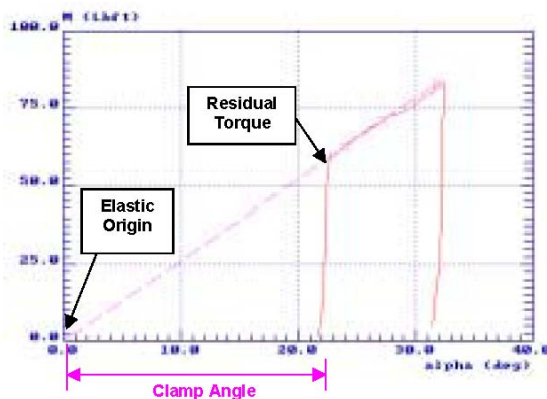


Fig. 3 — M-Alpha diagram of residual torque audit.

The point where the projected tangent crosses the zero or prevailing torque level is known as the elastic origin. The elastic origin acts as a reference point at which the angular displacement measurement begins. This angular measurement is known as the clamp angle, and is typically expressed in degrees of rotation of the moving member. As long as the projected line is tangent to the elastic portion of the torque-angle curve, the clamp angle measurement will be directly proportional to the tension in the fastener. When a tension-angle relationship is determined (clamp load/degree) the actual tension in the joint can be monitored.

The key to monitoring tension in a joint audit requires that the operator knows how much clamp load is produced for each degree of rotation. This relationship is determined by experimental testing of the joint in question, typically using some sort of clamp load measuring equipment. The process of qualifying the joint and determining the tension/torque/angle relationship is described in the following paragraphs.

Joint Qualification

Qualifying a joint consists of determining the amount of tension attained at a given torque value and relating the tension to the angular displacement of the bolt. Typically, a simulated joint is setup to replicate the joint stiffness and frictional characteristics, and the torque, tension and angle values are monitored. A number of installations are performed to gain confidence in the experimental values. It is important to use a continuous drive method such as with a dc electric drive motor to qualify joints in order to minimize torque losses.

Figure 4 represents a joint being qualified. The joint was tightened to 60 lb-ft (81 N-m), producing 7500 lb (33.4 kN) of tension.

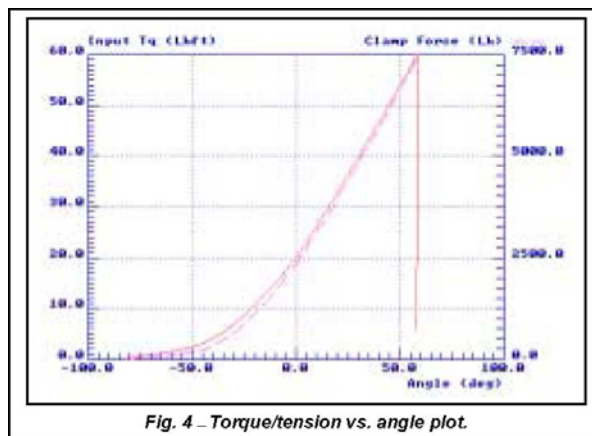


Fig. 4 – Torque/tension vs. angle plot.

Notice the similarities in the slope of the linear portion of the torque (solid line) and tension (dashed line) curves. In this region, known as the elastic tightening zone, the bolt stretch is described by a linear function and will be very consistent from joint to joint for joints with controlled initial stiffness and friction characteristics.

This consistency provides very predictable results once the relationship between torque, tension and angle is developed, thus the analysis will be performed in the linear portion of the signature. The curve will stay linear until either a friction or stiffness change occurs such as underhead embedment or bolt yield.

In the qualifying stage, the M-Alpha method is used to determine the torque-angle and tension-angle coefficients, the factors that relate torque and tension via the angle of rotation. Looking at the torque-angle signature from Figure 4, two points on the linear portion of the curve are picked off in the upper range of the linear portion of the curve as shown in Figure 5.

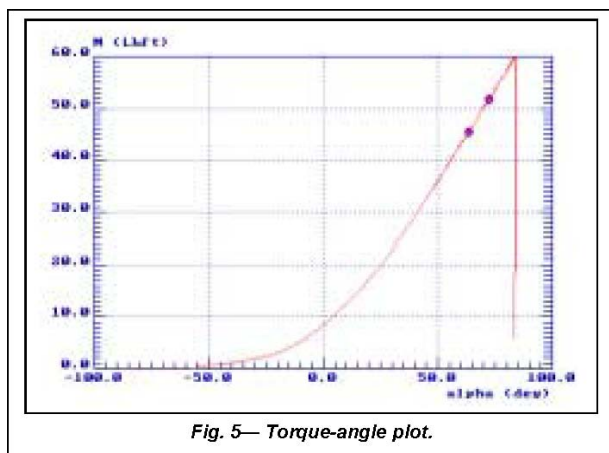


Fig. 5— Torque-angle plot.

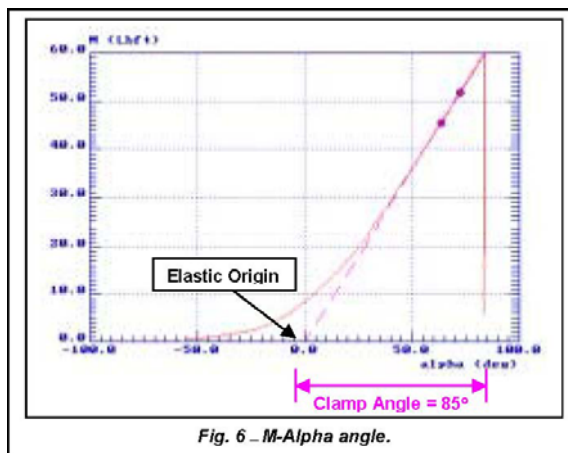


Fig. 6 – M-Alpha angle.

You then project a tangent line through the two points to the zero or prevailing torque level as shown in Figure 6.

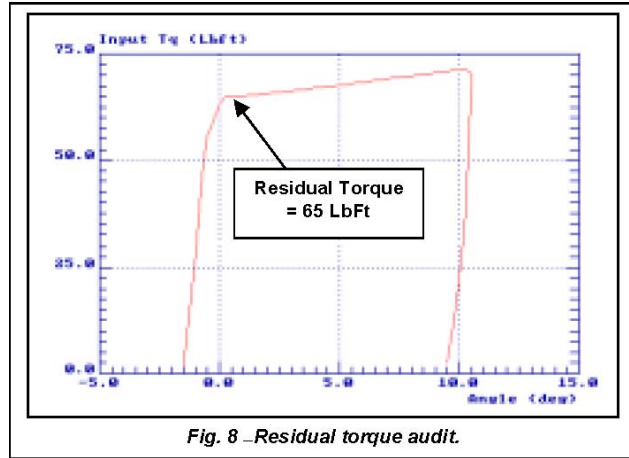
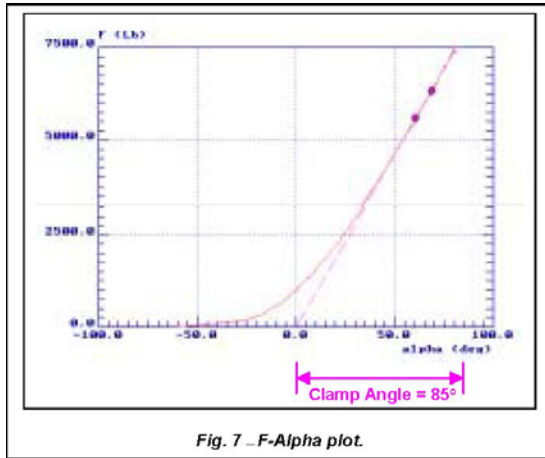
The point where the projected line crosses the zero/prevaling torque level is known as the elastic origin. From this point the angular displacement is measured ending at the final torque level. This angle measurement is known as the clamp angle. This plot is referred to as the M-Alpha diagram.

The clamp angle from Figure 6 is measured to be 85 degrees. From Figure 4 the tension is known as 7500 lb (33.4 kN) at 60 lb-ft (81 N-m). Therefore, in order to achieve 7500 lb of clamp load in the joint, 85 degrees of bolt rotation is needed from the elastic origin for the initial installation. The torque-angle and tension-angle coefficients can be determined by the ratio of torque and tension per degree of rotation, the slope of the tangent line.

$$\begin{aligned} 7500 \text{ lb}/85 \text{ degrees} &= 88.2 \text{ lb/degree} = \text{Tension-Angle Coefficient} \\ 33.4 \text{ kN}/85 \text{ degrees} &= 0.39 \text{ kN/degree} = \text{Tension-Angle Coefficient} \\ 60 \text{ lb-ft}/85 \text{ degrees} &= 0.7 \text{ lb-ft/degree} = \text{Torque-Angle Coefficient} \\ 81 \text{ N-m}/85 \text{ degrees} &= 0.96 \text{ N-m/degree} = \text{Torque-Angle Coefficient} \end{aligned}$$

The tension-angle coefficient can be verified by using the above methods on the tension-angle curve as shown in Figure 7. This is the companion diagram to the M-Alpha plot called the F-Alpha diagram. Similarly, a tangent line is projected from the elastic region of the curve to the zero/prevaling level and the clamp angle is measured from the elastic origin to the final clamp load value.

The F-Alpha plot provides a more accurate clamp angle since the frictional effects on the slope of the elastic region on the curve are eliminated.



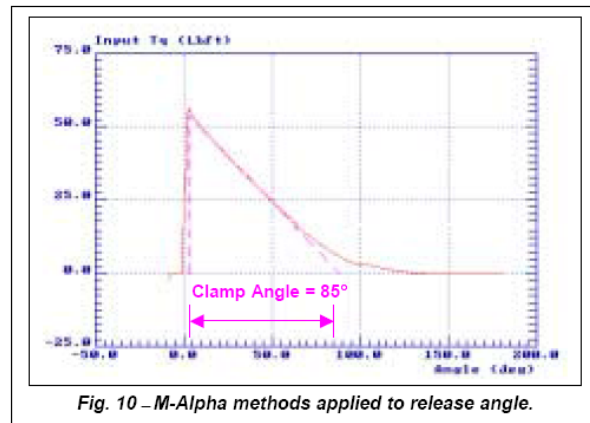
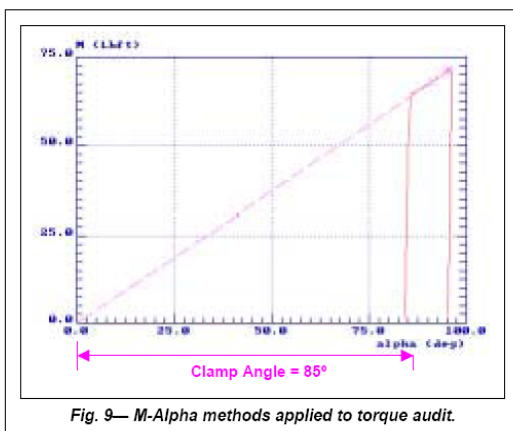
Analyzing the Audit

Once a joint has been qualified, a more complete audit can be performed. The process consists of performing a residual torque audit and analyzing the torque-angle signature. From the audit, the actual residual torque value can be found as well as the tension in the joint. The residual torque can be monitored by simple inspection of the audit plot. In order to determine the amount of clamp load in the joint, the operator can apply the M-Alpha method, that is, find the elastic origin and clamp angle on the signature and multiply the clamp angle by the tension-angle coefficient.

Figure 8 shows an example of a torque-angle signature of a residual torque audit and how the actual residual torque value can be measured.

The inspection of the residual torque audit will also indicate if the joint is in a state of yield, such as bolt deformation or underhead embedment. This is the case if the tightening portion of the curve is not linear or if the slope deviates from the qualified slope. It is important that the residual torque audit advances the fastener a minimal amount so that joint yielding does not occur and a true clamp angle can be read.

Figure 9 applies the M-Alpha method to the residual torque audit to determine the clamp angle. Note that the data is the same as in Figure 8, but that the expansion of the graph back to the elastic origin changes the appearance of the slope.



The audit in Figure 9 shows a clamp angle of 85 degrees with a residual torque value of 65 lb-ft (88 N-m). When the clamp angle is multiplied by the tension-angle coefficient of (88.2 lb/deg) or (0.39 kN/deg), the clamp load can be estimated at 7500 lb or 33.4 kN. This tells us that even though the residual torque value increased, the actual clamp load in the joint has remained the same. The increase in torque can be attributed to overcoming the static friction before angular rotation advances.

M-Alpha methods can also be performed on release audits to determine the amount of tension in the joint. Figure 10 shows the M-Alpha method being applied to the release audit of a similar fastener.

Application of the M-Alpha Auditing Process

The M-Alpha process can be applied to practically any bolted joint that needs auditing. When the tension-angle coefficient is established through some experimental pre-work, the tension in the joint can be audited without modifying the test joint. This can replace the need for strain-gaging bolts to try to determine the amount of clamp load in the joint. If the tension-angle coefficient is not known, the process can still be used to compare clamp load characteristics between fastenings through the clamping angle. This can be helpful if different coatings are being used on the same joint. The frictional changes in the joint can be seen through torque and angle deviations when applying M-Alpha analysis methods on residual torque audits.

M-Alpha audits were conducted on experimental joints and actual assemblies to determine how the heating and cooling cycles affected the frictional characteristics of a wheel nut application. These audits point out the value of the M-Alpha method for applications where the validity of traditional torque-only audits is affected by frictional characteristics. As with most applications, the torque applied to a wheel nut must overcome friction, Figure 11. The torque is broken down into three parts: underhead friction, thread friction, and pitch torque (the torque used to produce tension). Figure 12 shows the elastic region of a torque-angle signature projected back to the elastic origin and breaks out the torque values.

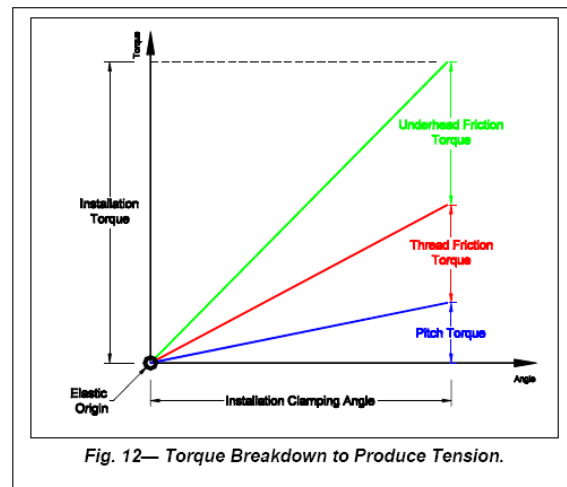
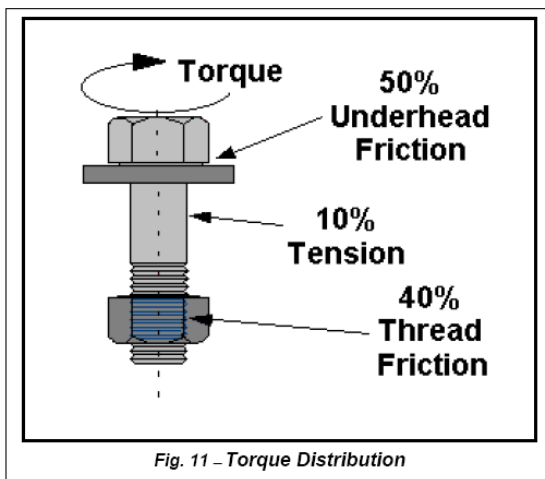


Figure 12 provides an overall representation of the installation process on a test joint, showing the relative amount of torque siphoned off due to frictional effects and how much energy was left to develop clamping force. It is important to examine what happens when the joint is put into service. After subjecting the joint to stress and heat cycles, the clamp angle will either stay the same or decrease, while the residual torque can increase, decrease, or remain the same. Since the joint stiffness and geometry will remain relatively the same, the changes mentioned above are due to friction changes.

Generally, thread friction deviations can be considered negligible in wheel nuts due to the large amount of bearing surface used (based on multiple installation torque-tension studies). Therefore, only underhead friction changes will be discussed. The following paragraphs explain these frictional changes as analyzed by M-Alpha methods.

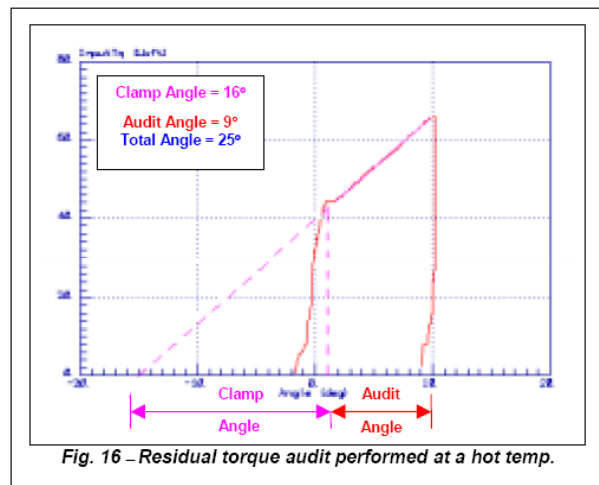
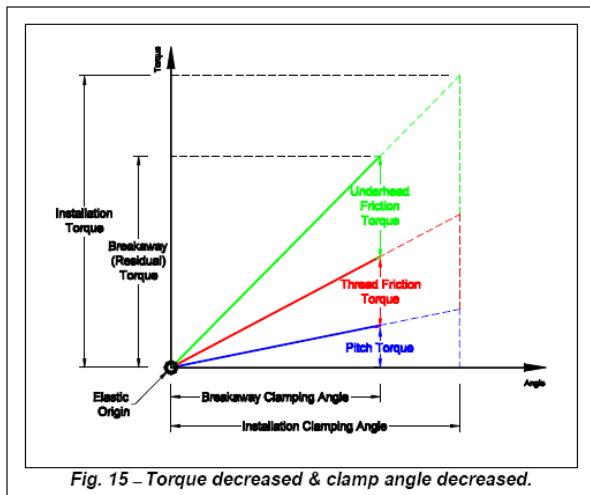
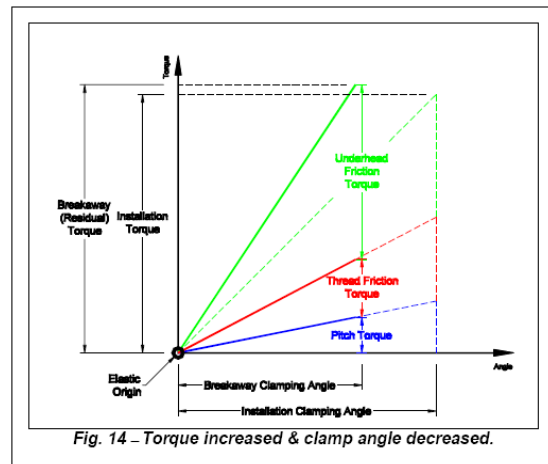
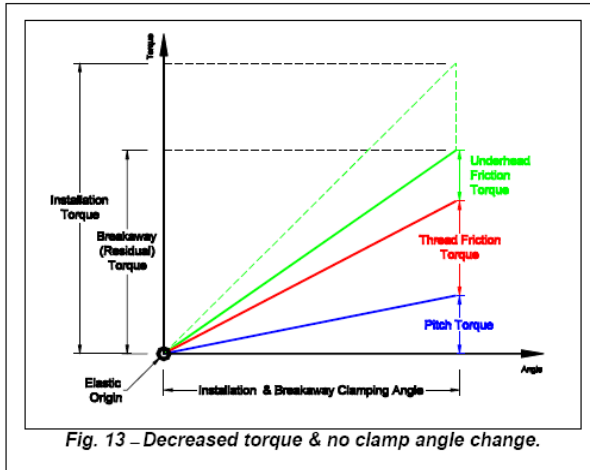
NOTE: The following analysis assumes that the installation process did not put the bolted joint into a state of yield.

Decreased torque and no clamp angle change. After performing an audit, if the torque value decreased but the clamp angle remains unchanged, the underhead friction decreased as shown in Figure 13.

The scenario illustrated in Figure 13 indicates that the tension in the joint remained unchanged, but the change in underhead friction may lead to slipping.

Torque increase and clamp angle decreased. After performing an audit, if the torque value increased and the clamp angle decreased, the underhead friction increased as shown in Figure 14. This indicates that the tension in the joint decreased. The increase in underhead friction may be due to some sort of curing between the fastener and the joint from heat cycles, or bearing surface disparities from the working loads. However, this does not mean that the clamp load increased.

Torque decreased and clamp angle decreased. After performing an audit, if both the residual torque value and the clamp angle decreased, then the underhead friction decreased as shown in Figure 15. This indicates that the tension and the underhead friction in the joint decreased. The decrease in underhead friction could lead to slipping.



Joints of Various Temperatures

The next series of examples use the M-Alpha auditing method on actual wheel joints performed at various temperatures. The wheels were track tested and taken through heat cycles to determine the residual clamping effects. These clamping effects were compared at the initial hot temperature and at room temperature. Residual torque audits were first performed at the hot temperature to get a reference clamp angle. Release audits were then performed, at hot and room temperatures, comparing the release angle to the clamp angle. Figure 16 shows a residual torque audit performed while the wheel joint was still hot from a high-speed braking test.

The clamp angle is 16 degrees. This is added to the extra angle of turn due to the audit (9 degrees) giving a total angle of 25 degrees at 66 lb-ft (89.5 N-m). Figure 17 shows the release angle performed on the joint from Figure 16 after the joint had cooled to room temperature. The torque broke away at 63 lb-ft (85.4 N-m) with a release angle of 25 degrees. Comparing this to the residual torque audit shows that as the joint cooled the residual torque value decreased slightly, but the clamp angle was unchanged indicating no loss of clamp load.

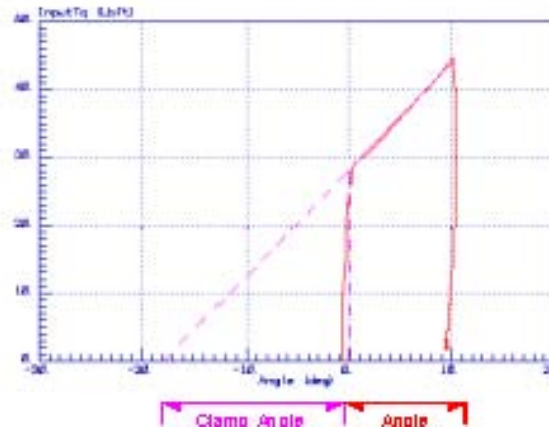
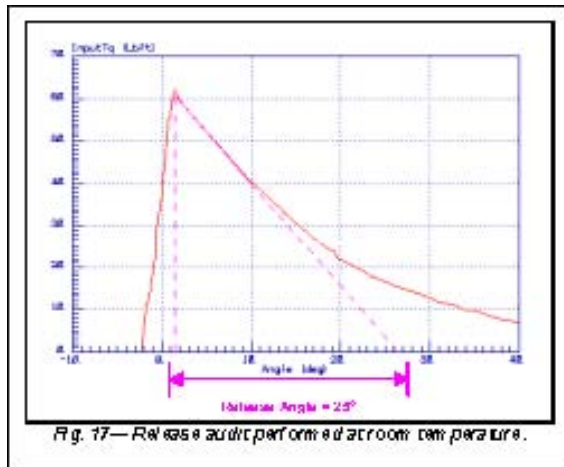
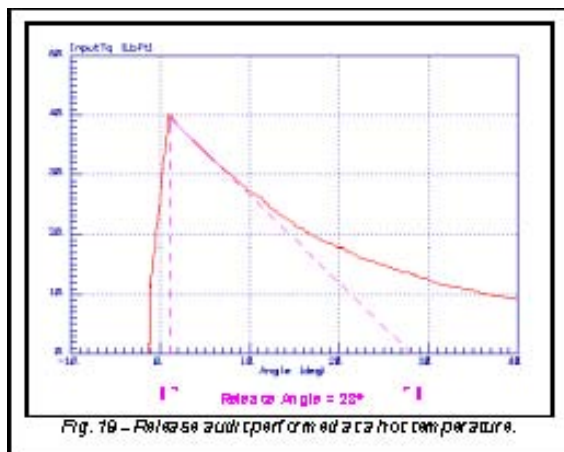


Figure 18 shows a residual torque audit of another joint performed while the joint was still hot. This gives a clamp angle of 18 degrees and an audit angle of 10 degrees giving a total angle of 28 degrees. The peak torque value of the audit is 45 lb-ft (61.0 N-m). Figure 19 shows the release audit, of Figure 18, performed at the initial hot temperature.



The torque broke away at 40 lb-ft (54.2 N-m) with a release angle of 28 degrees. This indicates, as compared to the residual torque audit data, that the clamp load remains unchanged even though the torque value decreased.

From this analysis, it can be seen that the temperature of the joint being audited has relatively no effect when it comes to clamp load values. Temperature changes will primarily affect the friction values changing the slope of the torque-angle signature. Therefore, when monitoring clamp load it really does not matter if the audit was performed while the joint was still hot from the testing or if it had a chance to cool. The torque value, however, will change due to the change in frictional characteristics in the joint as the temperature cycles.

When the joint, of the above example, is heated, the coating tends to act as a lubricant between the wheel surface and the nut. The torque audit performed at this heated state results in a lower torque value due to the decrease of underhead friction. Waiting for the joint to cool before auditing allows the coating to cool and possibly respond with a curing effect between the wheel and the nut producing similar torque values to the installation value (assuming no major torque loss when subjected to working loads).

The M-Alpha method of auditing considers the torque and the angle of turn from the projected elastic origin, which takes the temperature variable out of the picture (assuming a consistent rate of thermal expansion throughout the joint). As long as no additional torque is applied to the joint, temperature variance causing a change in the residual torque value will only change the slope of the line projected from the audit and will not change the angle of turn in the fastener. If there is no increase in angle of turn (no additional torque added to the joint) then the fastener will not be further stretched and the clamp load value will not change.

Conclusion

Auditing bolted joints by monitoring peak torque values from a residual torque audit does not provide enough information to determine the integrity of the joint. Variance in friction and auditing technique employed by the operator can significantly impact the amount of clamp load in a joint at a given torque value. For critical joints, additional information is needed from the audit to determine if the attained clamp load is capable of handling the working loads.

This is the Magic of M-Alpha: by monitoring torque and angle data and applying the M-Alpha method to determine the amount of clamp load in the joint, you can perform a more complete audit of your assembly; once you have established the tension/torque/angle relationship, you can estimate clamp load and determine the residual torque value by using only the torque-angle signature of a residual torque audit.

To further your understanding of a critical bolted joint, the M-Alpha analysis method can help you determine any frictional changes that develop between assembly and audit through the examination of assembly and audit torque-angle signatures. By properly employing the Magic of M-Alpha, you can confidently determine the integrity and acceptability of the bolted joint.

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