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A performance comparison between cooled and uncooled infrared detectors for thermoelastic stress analysis

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This study compares the stress-measurement sensitivity of several commercially available vanadium-oxide microbolometers to a scientific grade cooled indium antimonide imager. The devices were tested under similar conditions on the same mechanically-loaded subjects; one a uniaxially loaded plate containing a circular hole and the other a representative aircraft wing-skin coupon. The microbolometers are shown to consistently outperform the cooled imager for scan durations of 1500 load cycles or more despite having noise equivalent temperature detectivities (NETD) that were inferior by factors of between approximately 2 and 6. This finding is significant in two respects: it suggests that an NETD specification has only limited value as a sensitivity metric for thermoelastic stress analysis and secondly it confirms that microbolometers are able to furnish high-fidelity stress measurements of a type traditionally associated with cooled infrared imagers which are generally more costly to acquire and more cumbersome to use.

Keywords: thermoelastic stress analysis; experimental mechanics; microbolometer; infrared imaging

1. Introduction

Infrared focal-plane arrays (FPA) were first used for thermoelastic stress analysis (TSA) a little over two decades ago.[1,2] Their arrival brought about significant improvements in the practicality of TSA. Chiefly, the technique no longer required inordinately long observation times, a disadvantage of the progenitor of modern TSA instruments, SPATE,[3] a device with a single mercury cadmium telluride detector that had to be raster-scanned over an object to form a stress image.[4] The shift to FPAs came with another important advantage. Unlike SPATE, whose detector was cooled with liquid nitrogen, the first of the FPA-based systems [1] was cooled by means of a closed-cycle Stirling engine. It meant that one no longer had to keep a supply of liquid nitrogen (something not trivially obtained) nor ensure that the dewar in SPATE did not run empty during a long scan. These inconveniences are now long forgotten but at the time were quite bothersome. However, while the FPA did much to improve the practical appeal of TSA it did relatively little to increase take-up of the method within the broader engineering community. Even now, some two decades on, recognition of TSA is still relatively poor and lags well behind methods such as digital image correlation, despite that method having an inferior stress sensitivity.[5]

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Precisely why TSA has somewhat languished is an interesting question that would no doubt attract a range of opinions, but two factors are generally beyond dispute and are still relevant today: cooled FPAs require a significant capital outlay,[6] and their size and mass make them cumbersome to use in comparison to other imaging technologies.[7,8] The ensuing question then is why rely on cooled FPAs when thermal detectors for instance are significantly cheaper, much smaller (see Table 1) and generally more rugged? A look at the respective raw performance specifications in Table 1 reveals some answers: thermal detectors are roughly half as sensitive, and their dynamic response is vastly inferior. While the specifications do bear this out, the empirical evidence from the few reported applications of microbolometer technology to TSA suggest that these numbers can paint a misleading picture. In [9] for example, a low-grade microbolometer and a cooled indium antimonide imager applied to the same subject produced virtually indistinguishable results despite a 5-fold difference in temperature sensitivity. At first glance this result might seem counterintuitive but it is entirely plausible if the noise intrinsic to the imagers is structurally different, a reasonable proposition given that fundamentally different transduction mechanisms are involved. The implications are potentially quite significant as if high-fidelity stress measurements can be achieved with imaging devices that are much lower in cost, far smaller and more rugged than the cooled detectors that presently dominate, it could pave the way for a much broader utilisation of TSA. In flagging this prospect one is also obliged to note that beyond observations of the type reported in [9] relatively little in fact is known about the stress-measurement sensitivity of microbolometers. The present study seeks to address this shortfall by investigating the stress-measurement performance of several commercially-available microbolometers under controlled test conditions involving a dynamically loaded test subject with a known stress distribution. The results are compared to baseline measurements obtained from a scientific grade cryogenically-cooled infrared imager.

1.1. Thermoelastic stress analysis

The thermoelastic effect describes a reversible coupling between mechanical and thermal energy summarised by the relation,[10]

<table>
<thead>
<tr>
<th>Device</th>
<th>FPA size (pixels)</th>
<th>Type</th>
<th>NETD nominal (mK)</th>
<th>Response time (ms)</th>
<th>Max. rate (Hz)</th>
<th>Lens f#</th>
<th>Mass (kg)</th>
<th>Volume ($10^{-3}$ m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Microbolometers</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A20 M</td>
<td>160 × 120</td>
<td>VOX</td>
<td>120</td>
<td>13.9</td>
<td>50</td>
<td>1.2</td>
<td>0.80</td>
<td>0.94</td>
</tr>
<tr>
<td>A325</td>
<td>320 × 240</td>
<td>VOX</td>
<td>50</td>
<td>10.0</td>
<td>60</td>
<td>1.3</td>
<td>0.70</td>
<td>0.83</td>
</tr>
<tr>
<td>A315</td>
<td>320 × 240</td>
<td>VOX</td>
<td>50</td>
<td>12.1</td>
<td>60</td>
<td>1.3</td>
<td>0.70</td>
<td>0.83</td>
</tr>
<tr>
<td>(A)</td>
<td></td>
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<tr>
<td>A315</td>
<td>320 × 240</td>
<td>VOX</td>
<td>50</td>
<td>15.4</td>
<td>60</td>
<td>1.3</td>
<td>0.70</td>
<td>0.83</td>
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<tr>
<td>A35</td>
<td>320 × 256</td>
<td>VOX</td>
<td>50</td>
<td>12.3</td>
<td>60</td>
<td>1.25</td>
<td>0.20</td>
<td>0.18</td>
</tr>
<tr>
<td><strong>Photon detector</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X6540</td>
<td>640 × 512</td>
<td>InSb</td>
<td>&lt;25</td>
<td>Variable</td>
<td>125</td>
<td>3</td>
<td>5.05</td>
<td>7.56</td>
</tr>
</tbody>
</table>

*a*20 mK typically [16].

*b*Integration time is variable from 500 ns to frame period.
\[ \Delta T = -\frac{\alpha}{\rho C_p} T \Delta (\sigma_1 + \sigma_2), \]  

(1)

where \( T \) is the temperature, \( \alpha \), \( C_p \), and \( \rho \) are the coefficient of thermal expansion, specific heat capacity at constant pressure and density respectively, \( \sigma_1 \) and \( \sigma_2 \) are the principal stresses, and \( \Delta \) denotes a change. For structural metals thermoelastic temperature fluctuations are of the order of 1–3 mK MPa\(^{-1}\). Variations of this scale pose a difficult measurement problem for radiometric sensors. Take for example a cooled indium antimonide (InSb) detector which if properly calibrated will have an noise equivalent temperature detectivities (NETD) of somewhere in the vicinity of 20 mK. The threshold stress sensitivity of a raw measurement furnished by such a device is \( \approx 6 \) MPa at best, which in the context of full-field stress analysis is not particularly good. There is however a redeeming aspect to the fact that thermoelastic temperature fluctuations are so small. It means that Equation 1 is effectively linear, which enables the sensitivity of a measurement to be significantly improved with some rudimentary signal processing. The following briefly explains how. Following from Equation (1) and under conditions outlined shortly, the thermoelastic response of an object to an applied load variation \( L(t) \) can be written as,

\[ T(x,y,t) = R(x,y) \ G(x,y) \ L(t), \]  

(2)

where \( T(x,y,t) \) is the temperature response, \( G(x,y) \) is the detector gain distribution and \( R(x,y) \) represents the stress distribution in the object under load. The key underlying assumptions here are: (i) that the structure is not at resonance, which is true in most cases as TSA tends to be applied at loading frequencies below the first resonance, (ii) that higher order thermoelastic effects are negligibly small, which is always true (see e.g. [11]), (iii) that the dynamics of the infrared detector are taken into account (e.g. [9]) and (iv) that the effects of conduction, radiation and convection are insignificant. This latter condition normally holds true for radiation and convection, largely because the temperature fluctuations occur over a relatively short time scale and are small in absolute terms (i.e. \(<1 \) K) (see [4]). Conduction is an exception. Its effects are often significant and this leads to a violation of Equation (2) that needs to be taken into account when assessing a thermoelastic response measurement (see e.g. [12]). This point can be left aside for the moment though it will be re-examined later. By stripping \( L(t) \) of any offset, and assuming \( G(x,y) \) is a constant, i.e. each detector in the focal plane array has an identical gain, one can show that,[13]

\[ R_{ij} = \frac{\sum_{k=1}^{N} T_{ijk} L_k}{\sum_{k=1}^{N} L_k^2}, \]  

(3)

where the switch to subscript notation, i.e. \( i,j \) for \( x,y \) and \( k \) for \( t \), conveys the fact that the measured quantities are discretely sampled. By inspection of Equation (3) it is clear that \( R_{ij} \) retains only those components of the signal that are correlated with the load, i.e primarily the thermoelastic response. In the case where the only extraneous component of the signal is random noise one can show that the standard deviation of the noise in
$R_{ij}$ declines as an inverse function of $\sqrt{N}$. The noise in infrared FPAs is of course not all random; it also contains a systematic element referred to as fixed-pattern noise (FPN) which can be either additive or multiplicative.[14] The latter, which manifests as a non-constant $G(x, y)$, is clearly the worst kind for a thermoelastic response measurement since Equation 2 shows that it is, in general, indistinguishable from the term $R(x, y)$, i.e. it corrupts the stress measurement. As an aside it is somewhat ironic that having led to the demise of SPATE, FPAs were not able to match that device for high sensitivity applications, due largely to FPN problems.[15]

2. Experimental study

The devices investigated in the present study are listed in Table 1. Apart from the detector response times, which were measured using the procedure outlined in [9], the specifications given in the table were sourced from information supplied by the manufacturer.[16]

In order to conduct an assessment of the noise performance of a stress-imaging device one obviously needs a scene with a stable stress-field, but it is additionally helpful if the stress-field is spatially uniform, as will be explained shortly. Having said that, numerical scores obtained on a uniform test subject are not particularly instructive on the significance of performance differences; that is, whether a given margin in performance is likely to be noticeable and indeed useful in a practical application. A perturbation in the stress-field obviously helps in obtaining the requisite insights. Both requirements were considered when selecting the mechanical test coupons, of which there were two. The first, Figure 1(a), is a Al2024-T351 alloy plate containing a circular hole. The second, Figure 1(b), is a facsimile of the lower wing skin structure of the F-111C aircraft and specifically a small section just beyond mid span of the wing where cracking has occurred in fleet aircraft.[17]

The primary focus of the investigation is on the simpler coupon in Figure 1(a), henceforth referred to as specimen (a), and specifically on the thermoelastic response in the area marked $A$ which is a square shaped region with a side dimension of 36 mm. The area was imaged at a resolution of 0.36 mm which involved tailoring the field of view of each device such that the area was observed by a $100 \times 100$ sub-region of the FPA. While the stress-field within $A$ is relatively uniform, the thermoelastic scan in Figure 1(a) shows a slight residual influence from the hole that corresponds to approximately an 8% variation between the maximum and minimum stress. Since the investigation seeks to compare stress-sensitivity levels in a relative sense only, the removal of a fixed and stable trend of this type is not a strict necessity, however doing so is useful as it ensures that the primary source of variance in the measured response data is noise from the imager. The trend was eliminated by subtracting the first five terms of the quadratic function $c_1 x^2 + c_2 y^2 + c_3 xy + c_4 x + c_5 y + c_6$ where the coefficients were determined by a least squares fit to the data in $A$. Having reduced the signal to a nominally uniform value one then obtains a non-dimensional metric for the stress-sensitivity directly from the coefficient of variation,

$$c_v = \frac{\sigma}{\mu} = \sqrt{\frac{\sum_{i=1}^{N} (R_{i,j} - \bar{R}_{i,j})^2}{\sum_{i=1}^{N} R_{i,j}}}$$

(4)
where $\mu$ is the mean of the thermoelastic response signal and $\sigma$ is the standard deviation of the noise over the sample population of 10,000 (i.e. $100 \times 100$). For later reference note that multiplying $c_v$ by the mean stress variation produces a dimensional metric for the stress sensitivity.

A thin coating of an ultra-flat kahki coloured paint was applied to the bare metallic surface of the specimen to ensure a high and uniform infrared emissivity. The specimen was then installed in a digitally controlled 100 kN servo-hydraulic machine and its position within the hydraulic grips adjusted to ensure the loading was aligned with the longitudinal axis of the specimen; verified by checking the transverse symmetry of the thermoelastic response (see Figure 1(a)). The machine was programmed to apply a persistent 5 Hz sinusoidal loading with a 4 kN amplitude about a 4 kN mean. Within the area of interest A this produces an oscillating bulk-stress variation of $\approx 26$ MPa. The choice of loading frequency was dictated mainly by an imperative to simply avoid extremes in loading rate where most problems in TSA tend to occur. For instance, very low rates (say $\ll 1$ Hz) can lead to severe signal attenuation (by conduction and convection mainly), whilst at high-rate extremes the paint layer starts to exert an influence on the thermoelastic response (see [18]). Given the desire for a spatially uniform
scene this clearly presents a problem if the layer has an uneven thickness. The chosen loading frequency of 5 Hz is well away from either of these extremes.

Each imager was tested in the same manner. The thermoelastic response $R_y$ was recorded as a function of the cumulative number of loading cycles, at intervals of 5 cycles for the first 4 samples and 20 cycles thereon up to the conclusion of the test at 10,000 load cycles.

### 2.1. Imager settings

While the dynamic response of a thermal detector is determined by its physical properties, for a photon detector it is a function of the integration time which one can normally adjust in a modern imager. Since integration time is obviously a key determinant in noise performance, the X6540 sc was tested at several settings, namely 0.5, 1.0 and 2 ms; the latter corresponding approximately to the mid-well condition at 293 K, the approximate average temperature of the test specimen. Frame rate is another variable, however its effect on noise performance is predictable so testing was able to be confined to one rate. The rate chosen was 60 Hz which is consistent with the microbolometers apart from the A20 M which operates at 50 Hz.

Non-uniformity correction (NUC) is applied in both photon detector and microbolometer FPAs as a means of compensating for variations in detector offset and gain. The X6540 sc employs a proprietary procedure termed Continuous Non-Uniformity Correction (CNUC),[16] which relies on a factory-assigned mapping of gain and offset corrections specific to the selected integration time. This is a departure from traditional practice which involves a user initiated two-point calibration against either an internal or external reference. The microbolometers in the study use two different approaches. The A35 relies on firmware for both its offset and gain correction. All other devices employ an internal mechanical device called a NUC paddle which is flagged in front of the detector during offset calibration. This process is normally controlled through firmware however to ensure that flagging events did not occur during a thermoelastic response measurement NUC in the present study was controlled by external software. It was performed at intervals of 4 s, which is relatively short but this was thought a sensible precaution as the influence of microbolometer NUC on stress sensitivity was a priori unknown. Later on it is shown that the process has only a minor influence. Finally, the A315 and A325 units have a performance-related setting called ‘noise-reduction’ which, as the name suggests, serves to improve the quality of raw output. This function had to be disabled for this investigation as testing revealed that it had a profoundly deleterious effect on stress-measurement performance.

### 3. Results and discussion

Figure 2 summarises the noise performance of all six devices. The $c_v$ is plotted against the cumulative number of load cycles in this and all subsequent graphs. The choice of abscissa is somewhat arbitrary; one could just as well have plotted it against the cumulative observation time (linearly related via the loading frequency), or the cumulative number of images which is simply the observation time multiplied by the frame rate. Turning attention to the starting values for each curve these should in theory largely correspond to the detector NETD, that is a better NETD should produce a lower starting $c_v$. The results are for the most part consistent with this. In other words, the photon detector records the lowest initial value and the microbolometers cluster around an
average level a factor of between 2 and 3 higher, which, allowing for the small sample size fits broadly in line with the NETD specifications listed in Table 1. The A20 M is an exception, however this was later explained when measurements revealed that its actual NETD was much better than its specification.

Differences in the rate of decline in noise are of more significant interest. Consider first the X6540 sc results. Notwithstanding the wide separation between the three curves, all show a similar asymptotic form. A tapering rate of decline is indicative of FPN which is known to account for a significant proportion of the noise in cooled FPA’s [19–21]. By contrast the trend in the microbolometer data is close to log-linear over the considered range. This difference in behaviour eventually leads to intersections between the two sets of curves. In relation to the best of the X6540 sc results (i.e. the 2 ms case) these intersections occur at between 1500 and 4500 load cycles. Remarkably, the A20 M, a device over a decade old and long obsolete, accounts for the earliest intersection, and by completion of the test records a $c_v$ value some 30% better (lower) than the level achieved by the X6540 sc, and ranks second behind the A315 (A) as the best performing device.

Consider next the effect of integration time. As expected, the largest value produces the best performance, and one would expect by extension that the lowest setting should produce the worst. According to the results this is not so. The highest $c_v$ at scan completion was in fact recorded for the 1 ms setting. Given the odd nature of this result the scans were repeated, producing virtually the same result. The most plausible explanation is a deficient NUC producing an abnormally bad gain non-uniformity at that particular setting.

Figure 3 provides a slightly different perspective on the results. The traces here correspond to the standard deviation of the noise normalised to a value of one at the first scan point, i.e. at 5 load cycles. The absence of large offset variations of the type seen in the previous figure helps to clarify the improvement in signal quality achieved by each device. The dashed line corresponds to a $\sqrt{n}$ model and describes the response of an ideal detector after cross-correlation is applied to its signal, which is a useful reference. That this line is largely concealed by the microbolometer traces confirms that the noise is predominantly random.
3.1. A model for signal improvement

With two of the microbolometer traces still following a largely log-linear trend by the conclusion of testing, it was thought instructive to see how much further improvement might be possible with additional observation time. The A315 (A), as the best performing device, was selected for an extended test where the scan was allowed to proceed until the rate of decline in $c_v$ was clearly asymptotic, a point reached at some 50,000 load cycles. Figure 4 compares the trace to the best of the X6540 sc results. The decline in $c_v$ beyond $10^4$ cycles amounts to about an additional 30% of improvement, which is well below the $\sqrt{n_l}$ rate sustained to that point.

An asymptotic rate is no surprise as uncooled FPAs are of course not immune to FPN.[22] What this means is that although rates of decline might differ the curves in overall form are virtually identical. This suggests a consistent pattern to the signal

![Figure 3](image-url)  
**Figure 3.** Signal improvement expressed as a ratio with respect to the standard deviation after five cycles of cross-correlation.

![Figure 4](image-url)  
**Figure 4.** As in Figure 2 but for a five fold increase in scan duration.
improvement. One can capture the essential behaviour with a simple model of the type depicted graphically in Figure 5. The noise performance is shown to be determined by essentially three factors; (i) an upper bound dictated mainly by random noise intrinsic to the device, which is closely related to the NETD,[20] (ii) a lower bound set by the FPN after NUC and (iii) a \( n_i^{-0.5} \) bound on the rate of improvement by cross-correlation (Equation (3)). This model usefully sets out the fundamental limitations of NETD as a predictive parameter for the stress-measurement sensitivity.

3.2. Practical significance

The data presented thus far provides an objective measure of comparative noise performance but is not particularly effective in conveying the practical significance of the differences. The present section sets out to do this in two ways: firstly by reconsidering the \( c_v \) values in an appropriately scaled form and secondly by comparing the subjective quality of scans of the structural features in the two specimens.

Multiplying \( c_v \) by the bulk-stress variation in the region of interest yields an estimate for the standard deviation of the noise in terms of bulk stress, denoted by the symbol \( \sigma_b \), a parameter that can be thought of as a noise-equivalent stress sensitivity. The stress variation used in this conversion was deduced by hand calculation and then verified by three-dimensional finite-element analysis. Both methods furnished a value of \( \approx 26 \) MPa.

The converted values, shown in the last column in Table 2, confirm the A315 (A) as the most sensitive device and the X6540 sc as the least. In relative terms this represents a difference of over 30%, which is certainly not negligible, but when viewed in absolute terms the difference of 0.24 MPa is unlikely to be of great significant for the majority of applications, particularly those of an industrial persuasion. That judgment of course is case dependent and there are situations where small differences are potentially of vital importance, such as residual stress analysis[23] for instance. Indeed, the exceptionally good noise performance of the microbolometers in this study raise hopeful expectations for that application, a subject that warrants investigation.

The lack of correlation between the stress sensitivities and the corresponding NETD values shown in the first two columns of Table 2 supports previous assertions that an NETD specification provides little indication of threshold stress sensitivity. The
disparity between the nominal and measured values of NETD in the first four cases is also noteworthy, for several reasons. Firstly, it confirms that the ‘noise reduction’ facility in the A315 and A325 has a significant effect on NETD and is essential to achieving its rated specifications, a contrast to the deleterious effect it has on stress sensitivity, as mentioned previously. Another factor is that the measured NETDs were derived using a procedure slightly different to that prescribed by the manufacturer.\[16\] Neither procedure strictly adheres to the test method in the relevant standard,\[24\] however both use a consistent definition for NETD, viz.,

\[
NETD = \frac{\Delta T}{S/N} \tag{5}
\]

where \(\Delta T\) is the temperature difference between the object and the background and \(S/N\) is the signal to noise ratio. The deviations were: (i) the lens was retained on the camera and defocused, rather than removed and (ii) no allowance was made for ‘bad’ pixels. Both steps were deliberately made to ensure that each device was tested in a configuration that is more reflective of actual usage. Doing so obviously precludes a direct comparison to the published specification, however the measured values are quite close notwithstanding.

### 3.2.1. A qualitative comparison

Figure 6 compares scans of the hole region in specimen (a). The top row corresponds to 1000 load cycles which is equivalent to just over 3 min of cross-correlation. At this stage the X6540 sc should, according to Figure 2, have a signal to noise ratio advantage of about 30%. Visual inspection confirms a very slight difference in quality though this is only evident on close examination. In comparing image quality one also needs to be mindful of differences in spatial resolution. Two scans are shown for the X6540 sc, the first matching the resolution of the larger microbolometer arrays and the second at twice that, reflecting the two-fold advantage the photon imager has in FPA size. The higher resolution scan appears marginally better, but the difference is insignificant. This is not unsurprising as for many TSA applications it is heat diffusion rather than FPA size or the system IFOV (instantaneous field of view) specification that determines the amount of spatial detail in a scan. In the present case, there are simply no thermal features at a small enough length scale for the increased resolution to be a factor.
The scans in the bottom row, corresponding to 10,000 load cycles or just over 30 min of cross-correlation, paint a very different picture. Compared to the top row the image quality is much better overall, which is to be expected of course. However, the degree of improvement is noticeably greatest in the microbolometer scans which now surpass the X6540 sc results on almost every subjective measure of image quality. Interestingly, the distribution of the FPN in the X6540 sc scans is markedly uneven and much worse in the lower part of the frame (cf. the compressive stress lobe above and below the hole). This raises an interesting point. Since region A was in the ‘cleaner’ half of the FPA it follows that the comparisons in Figures 2–4 represent a best-case scenario for the X6540 sc, i.e. had A been located below the hole the noise performance metrics would have been comparatively much worse.

Recall that the A315 and A325 microbolometers were tested with NUC implemented at 4 s intervals. To examine whether such a short interval was necessary a test was done on the A315 (A) with its NUC disabled for the duration of the scan, meaning that no offset or gain corrections were applied once acquisition had begun. As seen in Figure 6 (scan third from the left) this step has had little noticeable effect on image quality suggesting a relatively stable gain over the half-hour duration of the scan. On this basis the 4 s NUC interval applied in the noise-performance study was probably unnecessarily short.

3.2.2. Comparative performance in an aerospace application

An examination of the aircraft wing-skin coupon shown in Figure 1(b) offers another useful perspective on how differences in performance translate to practical results. Figure 7 shows thermoelastic response measurements and a prediction of the bulk stress...
distribution from three-dimensional finite element analysis. The measurements correspond to a load amplitude of 20 kN (peak–peak) applied at 5 Hz using the same mechanical test machine described previously. The simulation was undertaken for a static load of 20 kN. The first four measurements (from left) correspond to an observation involving 1000 load cycles or just over 3 min of cross-correlation, and the last to 10,000 load cycles or just over 30 min of cross-correlation. The example serves several purposes. The first is to demonstrate that valuable engineering information can be obtained without recourse to the highest possible levels of stress sensitivity. In the present case the main engineering interest is in the scale of the stress concentration in the centre groove region, an area where a large crack was discovered in an Australian Defence Force F-111C aircraft.[17] From the viewpoint of assessing the criticality of the region the scans are largely interchangeable, i.e. that the groove creates a large stress concentration is readily deduced from any one of the measurements. In this sense the use of a cooled detector offers no advantage, and even if increased sensitivity were

Figure 7. Stress distribution in the wing-skin coupon shown in Figure 1(b). Compared are various thermoelastic response measurements and a prediction from three-dimensional finite element analysis. Scale is in MPa and numbers in parenthesis indicate the cross-correlation length in load cycles.

Figure 8. Shift applied to the X6540 sc data to simulate the effect of acquiring data at the maximum frame rate of the imager.
required any one of the microbolometers are capable of furnishing higher sensitivity given ample processing time (i.e. scan second from right in Figure 8). In the context of a fatigue-prone structure however extended testing might raise concerns about its impact on fatigue life. Without seeking to over-generalise such concerns are largely unfounded for the simple reason that one does not need to apply damaging load levels to elicit a measurable thermoelastic response in the critical area. The case at hand is a good example. The maximum load applied to the wing-skin coupon under representative flight-spectrum loading is over 200 kN, an order of magnitude higher than the maximum load applied in the present analysis. Given the stress sensitivities in Table 2, it is clear that even a 20 kN load was unnecessarily high.

3.3. General remarks

The discussion is concluded by setting out the primary limitations of the study and the extent to which they qualify the findings. Firstly, the study was limited to only a single cooled imager. While the device was state-of-the-art and relatively new (only several months old) at the time of the study, this does not dismiss the possibility that it was an unusually bad example. There is evidence to suggest it was not: namely that a measurement of its NETD against an area blackbody yielded a value within 3% of the manufacturer’s specification. However, as discussed previously an NETD measurement reveals little about the FPN performance so this offers only a qualified reassurance.

A further experimental limitation relates to loading frequency. It is conceivable that performance margins might change with higher loading frequencies because of the better dynamic response of a photon detector. A simple calculation illustrates why. Consider the respective gain functions,[9, 13]

\[ G_{\text{microbolometer}} = \frac{1}{\sqrt{1 + \omega^2 \tau^2}} \]  
\[ G_{\text{photon detector}} = \frac{1}{\omega \tau} \sqrt{2(1 - \cos \omega \tau)} \]  

where \( \omega \) is the angular frequency, \( \alpha \) is the microbolometer response time and \( \tau \) is the photon detector integration time. Taking the values of \( \alpha = 10 \) ms and \( \tau = 2 \) ms from the present study and inserting them in the equations for a frequency of 5 Hz, yields gains of 0.954 for the microbolometer and 0.999 for the photon detector, which are very similar. The gain function for the microbolometer however falls off more steeply with frequency. At 20 Hz for instance, the respective values are 0.623 and 0.997. The gap of course widens as the frequency increases. The relative noise performance of the microbolometer should deteriorate as a result. The extent to which it does is a possible subject for future investigation.

The final point to make relates to image frame rate. The frame rate controls the number of samples available for the cross-correlation process so has a direct bearing on the rate of improvement of the signal. A short experimental investigation confirmed that increasing the frame rate had the equivalent effect to a proportional increase in the number of loading cycles, as one would expect. Recall that in the present study the X6540 sc was operated at 60 Hz which is approximately half its maximum frame rate. As described previously this was done for consistency with the microbolometers.
in the knowledge that a variation in frame rate would simply shift the $c_v$ curve left or right by the proportional amount. Figure 2 illustrates the effect of a shift that accounts for an increase in the X6540 sc frame rate to its full-frame maximum of 125 Hz. As can be seen it delays the cross-over between the two devices by approximately 800 load cycles, which amounts to a little less than 3 min of additional processing for the microbolometer.

4. Conclusion

This study has compared the stress-measurement sensitivity of several commercially available vanadium-oxide microbolometers to a scientific grade cooled indium antimonide imager. When tested under similar conditions on the same mechanically-loaded subject, the microbolometers were shown to consistently outperform the cooled imager for scan durations of 1500 load cycles or more despite having NETDs that were inferior by factors of between approximately 2 and 6. This finding is significant in two respects: it suggests that an NETD specification has only limited value as a sensitivity metric for TSA and secondly it confirms that microbolometers are able to furnish high-fidelity stress measurements of a type traditionally associated with more costly and cumbersome cooled imagers.

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Note

1. A signal level at 50% of full dynamic range.

References


