Tethered drones: understanding rotor loads

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1. Menet Aero - 2. Wolf Star Technologies

Menet Aero of Oak Creek in Wisconsin in the USA creates a unique style of drone. It specializes in manufacturing tethered unmanned aircraft systems (TeUAS) or drones which provide secure, on-demand wireless communications. These high-performance platforms, designed in heavy and light configurations, support a variety of payloads for applications such as high-bandwidth digital battlefield communications, signal intelligence, electronic warfare, and force protection and targeting.

Menet Aero systems are used by the Army, Air Force, Navy, and Marines in the USA, and also by joint organizations for a variety of applications, including telecommunications, intelligence, surveillance, and reconnaissance (ISR).

Engineered from the start to be tethered systems, they are more rugged and last longer than battery systems that have been modified to use ground-based power through a tether. Menet Aero's TeUAS are powered via a tether that connects the aircraft to a power source, and can be integrated into various vehicles, trailers, vessels, and other platforms to provide seamless integration into the mission and battlefield. They accommodate payloads of up to 40lbs (18.143kg) and can be optimized to reach hover heights up to 1,000feet (304.8m) AGL (above ground level).

For these critical missions, Menet Aero wanted a higher fidelity understand of the loading on its drones in order to use these loads to design and optimize better aircraft. The company worked with Wolf Star Technologies to explore an initial implementation of Wolf Star's True-Load load reconstruction software on its hexacopter.
For the initial application, Menet and Wolf Star agreed to concentrate on just two of the six arms on the hexacopter to generate an initial understanding of the applicability of the technology while minimizing instrumentation logistics.

Menet hexacopters have carbon-fibre arms. The True-Load technology requires an FEA (fixed element analysis) model of the structure and will eventually need to place strain gauges on the arms.

As part of the development exploration into the application of the True-Load technology, Menet agreed to swap out the carbon-fibre arms with thin aluminium tubes. This would allow for easier FEA modelling and simpler strain gauge application. The plan is to follow up with a carbon-fibre FEA model and specialized carbon-fibre strain gauges once the demonstration has been successfully completed.

True-Load theory

True-Load load reconstruction works on structures that behave linearly during the event of interest. The structure can undergo non-linear behaviour prior to or after the event of interest. The term "linear" in this context means that the strain response is proportional to the applied loading. Portions of the structure may behave non-linearly. For example, local yielding near welds, bolted joints, or boundary conditions may undergo non-linear strain response. Load reconstruction will continue to be effective if the nominal portions of the structure undergo linear response to the applied loading. Structures with gross yielding will not be appropriate for load reconstruction. Schematically, the concept of linearity is illustrated in Fig. 1.

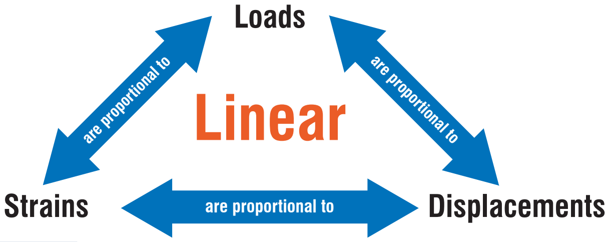

Fig. 1. Linear material behaviour schematic.

This linear relationship can be represented mathematically as follows:

$$F=Kx$$

Equation 1: Hooke's Law.

$$\varepsilon C=F$$

Equation 2: Influence coefficient equation.

Applying this strategy to field testing yields the following relationship:

Time Histories of Strain — Time Histories of Load

$$\begin{bmatrix} \varepsilon_{t_1,1} & \varepsilon_{t_1,2} & \vdots & \varepsilon_{t_1,m} \\ \varepsilon_{t_2,1} & \varepsilon_{t_2,2} & \vdots & \varepsilon_{t_2,m} \\ \cdots & \cdots & \ddots & \vdots \\ \varepsilon_{t_{end},1} & \varepsilon_{t_{end},2} & \cdots & \varepsilon_{t_{end},m} \end{bmatrix} [C_{m\,x\,n}] = \begin{bmatrix} F_{1_{t_1}} & F_{2_{t_1}} & \cdots & F_{n_{t_1}} \\ F_{1_{t_2}} & F_{2_{t_2}} & \cdots & F_{n_{t_2}} \\ \vdots & \vdots & \ddots & 0 \\ F_{1_{t_{end}}} & F_{2_{t_{end}}} & \cdots & F_{n_{t_{end}}} \end{bmatrix}$$

Equation 3: Time series coefficient equation.

The strain matrix on the left-hand side of the time series coefficient equation represents strain gauge values (reported in the columns) at each time point of data collection (reported in the rows). This is the strain data that was collected from a test event. The right-hand side of the equation represents a set of vectors for scaling each load case. When the individual load cases are scaled by each vector and the results are linearly superimposed, the resulting strains at the gauge locations of the corresponding row in the test strain matrix are guaranteed to match. Furthermore, any other response in the structure can be expanded backwards through this superposition.

True-Load application

To develop a True-Load application, one first constructs an FEA model with unit load cases representing the exterior loading. In the case of the Menet Aero hexacopter, we observed that the electric motors on the arm were exciting very high frequency modes. If these modes were not accounted for, the load calculations could be erroneous.

Fig. 2 shows the FEA model of the arm and the reference geometry. Note the FEA model of the arm is just a tube with remote attachments for masses and loads. The geometry for the prop and motor are shown only for graphical representation; they are represented only as point masses in the FEA model. Fig. 3 shows the unit loads on the FEA model. The True-Load software identifies optimal strain gauge placement. In this application, 12 strain gauges were used. Typically,

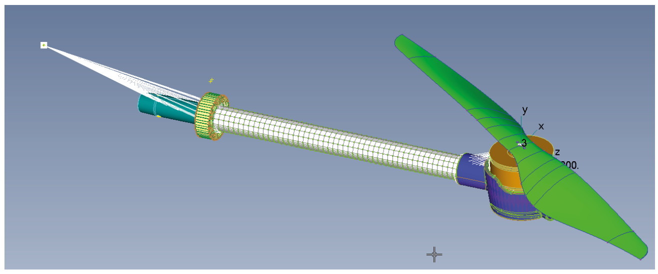

Fig. 2. FEA model of hexacopter arm.

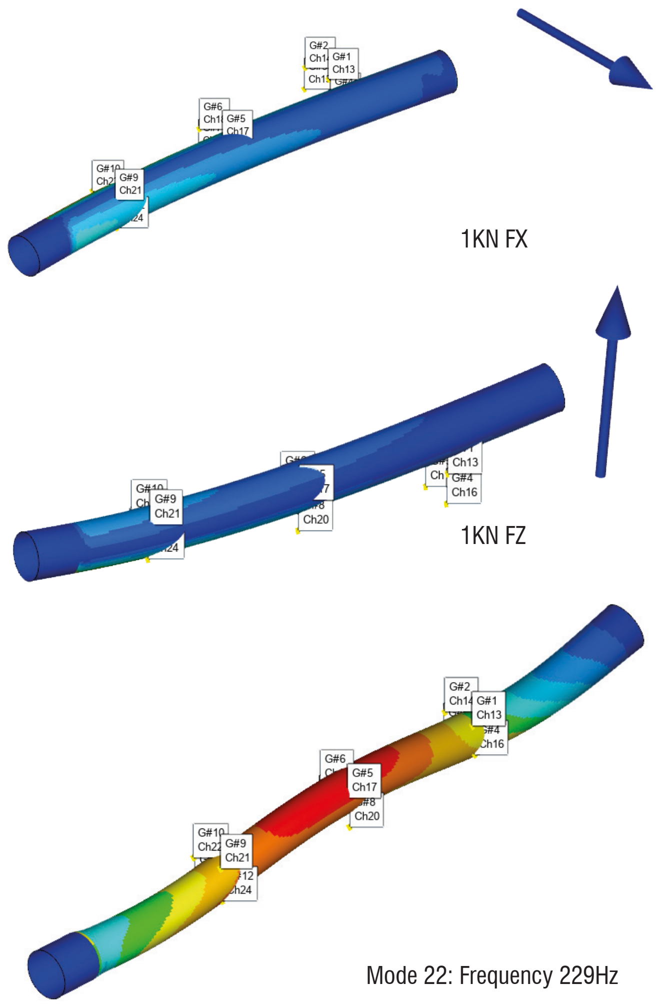

Fig. 3. Unit loads / modes used for True-Load.

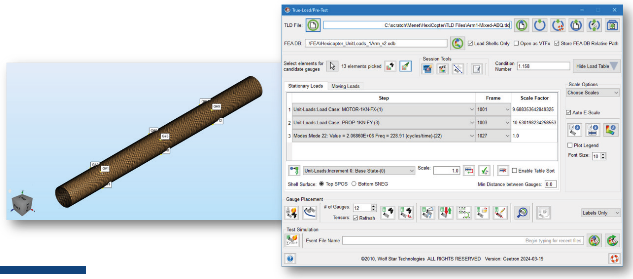

Fig. 4. Virtual gauge placement.

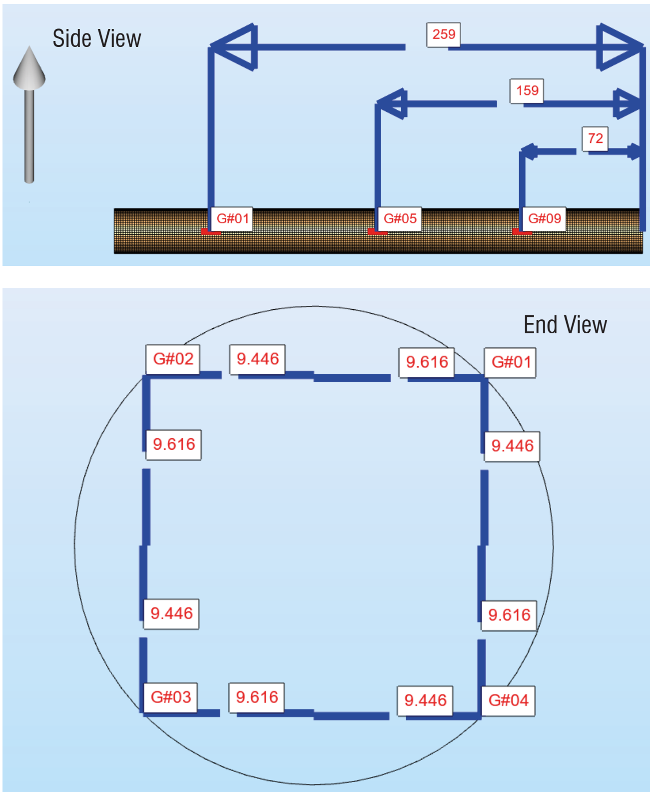

Fig. 5. Gauge dimensions.

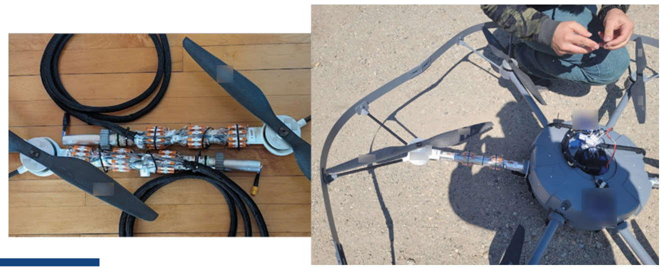

Fig. 6. Strain gauged arms and DTS DAQ mounted on the drone.

for an application of three-unit loads / modes, True-Load would require just six strain gauges. However, since this was a learning and discovery project, extra strain gauges were used. Specifically, three sets of four strain gauges were used. Fig. 4 shows the virtual strain gauge placement in True-Load.

Each set of four gauges was equally spaced around the circumference of the arm. Fig. 5 shows the gauge placement. Note that the gauges are not placed on the top and bottom fibres, but rather at 45° from the top and bottom fibres.

This allows all gauges to be active (non-zero) during testing. If gauges were aligned to the top and bottom fibres, then two other gauges would be on the neutral fibre and would thus theoretically read zero strain. The parts were then strain gauged and connected to a data acquisition system (DAQ). The DAQ used was a DTS Slice Micro. The DTS Slice Micro is extremely compact (45mm^3) and runs off a small external battery. It was programmed to sample at 2KHz and was then mounted onto the drone connected to the strain gauges (Fig. 6).

Several events were conducted and the DAQ measured the strain data. Over 30 events were measured. Fig. 7 shows the strain response from three of the 30 events. Note that the strain values have been blurred to protect Menet Aero's intellectual property.

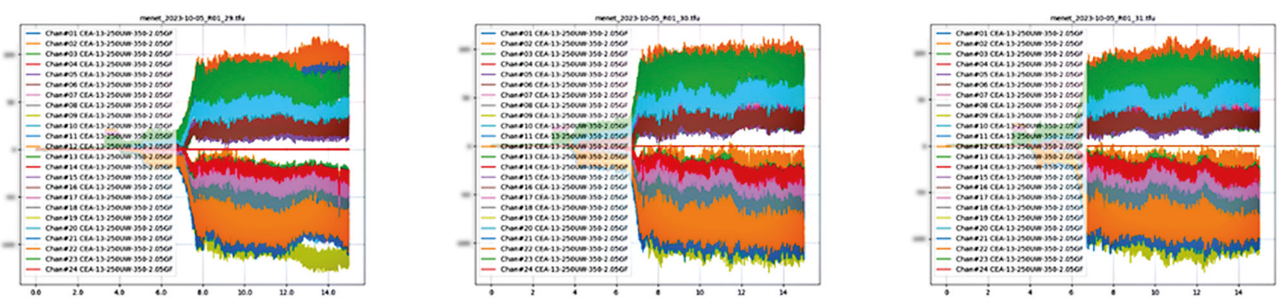

Fig. 7. Measured strain response.

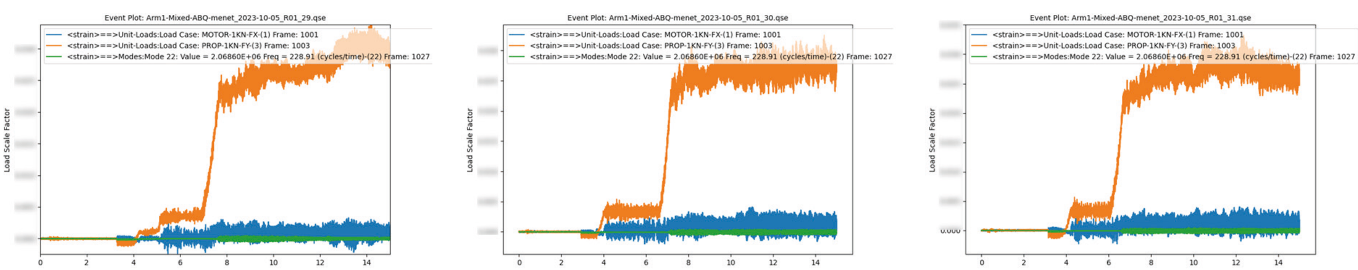

Fig. 8. Loads calculated from strain.

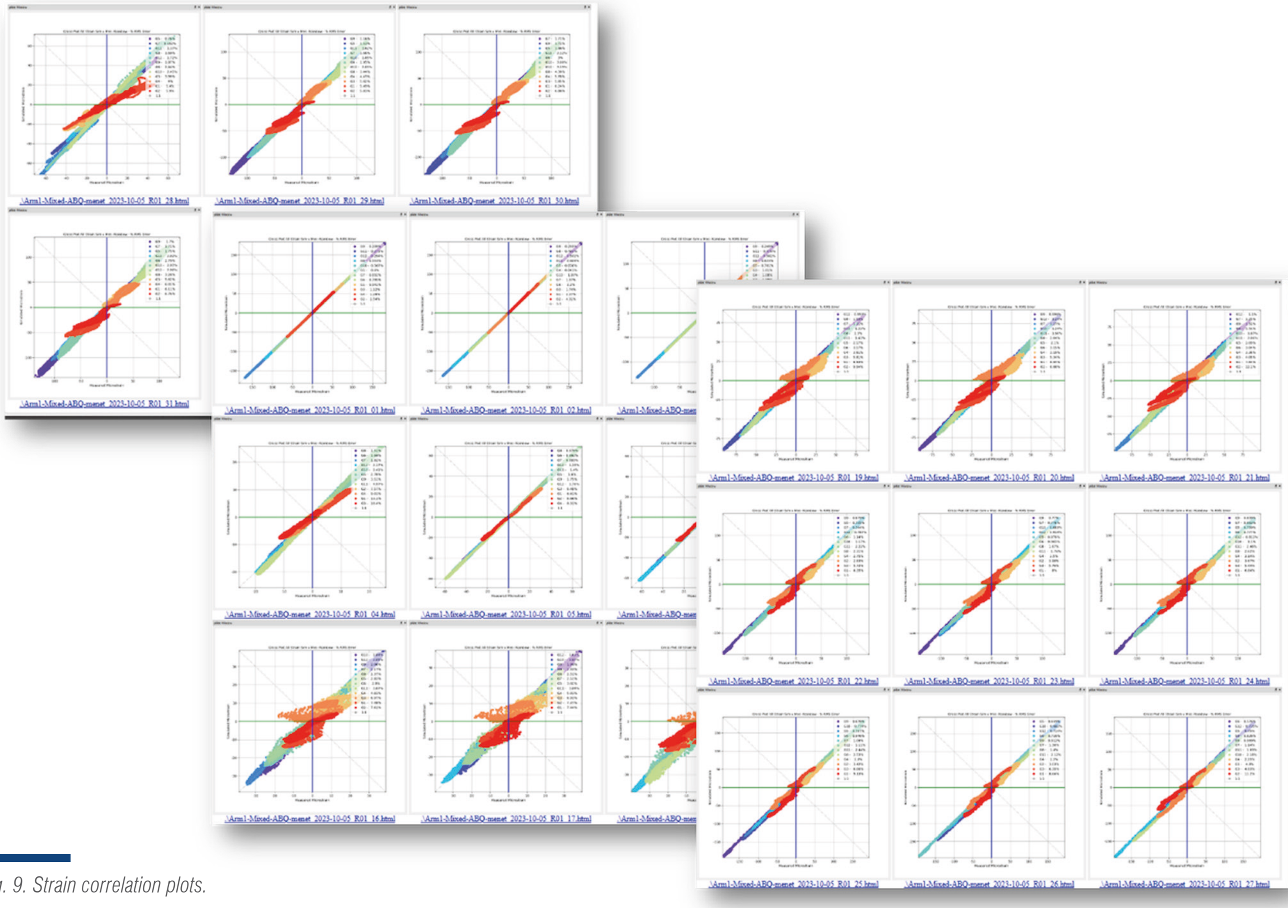

Fig. 9. Strain correlation plots.

The purpose of True-Load load reconstruction is to convert measured strain data into calculated operating loads. Fig. 8 shows the resulting load calculations for the strains measured in Fig. 7. The orange curve shows the lift force; the blue curve shows the tangential loads due to motor shaking; and the green curve shows the MPF of mode 22.

Fig. 9 shows the automatic strain correlation plots created by True-Load for all 30+ test events. The horizontal axis on the plots illustrates measured strain and the vertical axis represents simulated strain from loads calculated by True-Load. As can be seen the strain correlation is excellent. This informs us that the calculated strains are indeed the actual operating loads.

From this exercise Menet Aero now has the operational loads for its drone. The company can use these loads to optimize its drones for weight and cost. The True-Load methodology was an efficient and effective use of FEA models and testing techniques. For a small investment in strain gauges ($10/gauge), Menet acquired mission critical, valuable data on its designs.

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About Menet Aero

Menet Aero is an aerospace solutions provider specializing in manufacturing Tethered Unmanned Aircraft Systems (TeUAS) or drones. Our high-performance platforms, designed in heavy and light configurations, support a variety of payloads for applications such as high bandwidth digital battlefield communications, signal intelligence, electronic warfare, and force protection and targeting.

As a U.S. -owned and veteran-operated small business, we take pride in offering top-quality solutions to our customers.

About Wolf Star Technologies

Wolf Star Technologies specializes in globally proven, first-to-market software solutions that solve fundamental Product Development problems.

Their software packages, True-Load, True-QSE, and True-LDE are game-changers for Product Development. They extract decision ready data from FEA models and bring a unique understanding to the dynamic loading of structures.
To find out more, visit: www.wolfstartech.com