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Study on thrust force and torque sensor signals in drilling of Al/CFRP stacks for aeronautical applications

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Abstract

Multi-material stack products made of carbon fibre reinforce polymers (CFRP) and light-weight metal alloys, such as aluminium alloys, are becoming increasingly employed for aerospace applications. When composite laminates are stacked with metal alloy sheets, the drilling process becomes more complex due to the diverse properties of the stacked materials which involve different wear mechanisms and different drilling parameters. In this framework, the aim of this paper is to investigate the drilling process of Al/CFRP stacks for aeronautical applications through an experimental testing campaign under different drilling conditions. In order to study the thrust force and torque generated during the drilling process, a multiple sensor system is employed for data acquisition, and an advanced methodology for sensor signal processing in the time and frequency domain is developed.

Keywords: Al/CFRP stacks; Drilling; Sensor monitoring; Sensor signal processing

1. Introduction

The use of lightweight composite materials such as carbon fibre reinforced polymer (CFRP) composites is considerably growing in aeronautical applications. In aircraft design, an increasing amount of metal components are replaced by CFRP structures, e.g. parts of the fuselage, wing structure, flap track fairings, airbrake, etc. [1]. The major objective of CFRP integration in load bearing structures is the reduction of weight with consequent energy saving and higher fuel efficiency.

However, a complete replacement of metal components is not recommended as CFRP exhibit low bearing and shear strengths and high notch sensitivity [2]. Therefore, innovative hybrid structures for key load-bearing components made of composite laminates overlaid on light-weight metal alloy (e.g. aluminium or titanium alloy) sheets have been developed to take advantage of the convenient isotropic behaviour of metal alloys (to face the complex stress state of bolt loaded holes) and of the high strength to weight ratio of CFRP composites [2,3].

The use of such hybrid stacks is expanding for structural aerospace applications, especially where high mechanical loads exist, such as for aircraft wing and tail-plane components [4,5].

Fastening of composites to metallic parts in the assembly of aerospace components is still most widely carried out via mechanical bolting or riveting, that require preliminary drilling.

However, drilling of hybrid CFRP/metal alloy stacks is a challenging process due to the dissimilar mechanical and physical properties of the different materials involved and their diverse machinability. The drilling parameters for each material differ together with its wear mechanisms and there is a lack of knowledge on the optimal process parameters, tool geometries and materials for stacks made of dissimilar materials [4,6].

In this framework, the aim of this paper is to investigate the 'one shot' drilling process of Al/CFRP stacks for aeronautical applications through an experimental testing campaign under different drilling conditions with the employment of a multiple sensor system to monitor the process behaviour.

In order to study the thrust force and torque generated during

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the drilling process, appropriate sensors are employed for data acquisition, and an advanced methodology for sensor signal processing in the time and frequency domain is developed with the aim to investigate the trend with increasing number of holes and the correlation between sensorial features and tool wear.

2. Experimental tests on drilling of Al/CFRP stacks

The experimental drilling tests on Al/CFRP stacks were performed reproducing the aeronautical industry operating conditions. The equipment is composed by a CNC drill press provided with a clamping system for the stack samples to be drilled. A tungsten carbide twist drill bit was employed to realize 30 holes for each cutting condition. With the aim to study the tool wear development, the drill bit was removed after every 5 holes in order to measure the tool wear in terms of flank wear using an optical microscope.

2.1. Experimental setup: material, tool, machine tool

The workpiece employed is represented by Al/CFRP stack samples. The aluminium sheet, placed on the top of the stack, has a thickness of 2.5 mm and is made of 2024 alloy. The CFRP laminate, placed at the bottom of the stack, has a thickness of 5 mm and is made up of 26 prepreg unidirectional plies with stacking sequence $[\pm45_2/0/90_4/0/90/0_2]_s$. The prepreg plies are made of Toray T300 carbon fibre and CYCOM 977-2 epoxy matrix. A very thin fiberglass/epoxy ply (0°/90° fabric) is laid on the top and bottom of the CFRP laminate.

The laminates were fabricated by manual layup, vacuum bag moulding and curing in autoclave, generating a smoother surface on the mould side and a more irregular one on the bag side of each laminate. The hybrid stacks were built by positioning the bag side of the CFRP laminate in contact with the aluminium sheet. The utilized drill bit is a traditional tungsten carbide twist drill with 2 flutes, diameter of 6.35 mm, point angle of 125° and helix angle of 30°.

2.2. Drilling parameters

In order to test the drilling performances under different cutting conditions a brief literature review was carried out with the aim to highlight the current machining conditions employed in the drilling of Al/CFRP stacks. It was seen that the highest spindle speed used for drilling Al/CFRP stacks is 2750 rpm and the highest feed rate is 0.15 mm/rev [7]. With the aim to test severer drilling conditions in terms of spindle speed, the following values were selected for the experimental tests: 3000 rpm, 4500 rpm and 6000 rpm. As regards the feed, which is considered highly responsible for tool breakage, values comparable to those indicated in the literature were selected: 0.05 mm/rev, 0.10 mm/rev and 0.15 mm/rev.

Taking into account the tool wear behaviour, the best cutting conditions allowing for slower tool wear in CFRP drilling consist of lower speed and higher feed values, while the opposite stands for Al [8]. However, considering hole quality and delamination, lower feed values should be selected.

The different combinations of cutting parameters adopted for the Al/CFRP drilling tests are summarised in Table 1.

Table 1. Experimental testing conditions.

	Spindle Speed (rpm)		
Feed (mm/rev)	3000	4500	6000
0.05	X	X	X
0.10	X	X	O
0.15	X	X	O

2.3. Multiple sensor system

With the aim to investigate the thrust force and torque signals generated during Al/CFRP drilling, the CNC drill press was equipped with a multiple sensor system made of (Fig.1):

- Kistler 9257A piezoelectric dynamometer to acquire the thrust force along the z-direction, F_z.
- Kistler 9277-A25 piezoelectric dynamometer to acquire the cutting torque around the z axis, T.

The analogue signals acquired by the above sensors were digitalized at 10 kS/s sampling rate by a National Instrument NI USB-6361 DAQ board. This sampling rate was chosen based on the Nyquist-Shannon sampling theorem.

3. Sensor signal analysis procedure

The acquired signals were employed to investigate the Al/CFRP stack drilling process with particular reference to tool wear. To this aim, the objective of the sensor signal analysis procedure is to extract a number of significant sensor signal features which could be potentially correlated with the measured flank wear (VB) of the drill bit.

In order to extract the sensor signal features, the acquired signals were segmented with the aim to remove the parts which are not relevant for the analysis, such as before and after the actual tool-workpiece contact, and to preserve only those parts corresponding to the drilling phase [9–11].

The signal segmentation was driven by the thrust force signal which allows to more easily identify the actual duration of the machining process. The adopted segmentation procedure is the same described in a previous work by the authors [12].

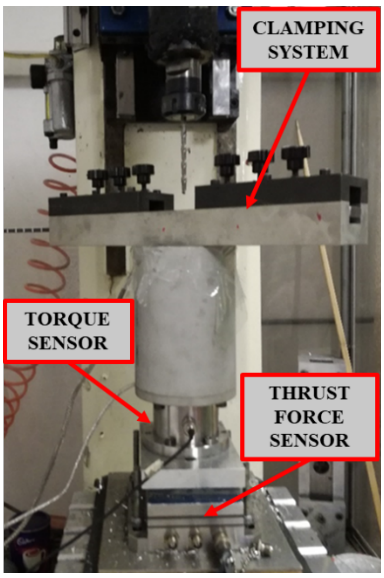

Fig. 1. Multiple sensor system mounted on CNC drill press.

After the segmentation procedure, two types of analysis were performed in order the extract the sensor signal features. The first one provides features extracted using statistical analysis in the time domain, whereas the second one provides features extracted via peaks analysis in the frequency domain. This analysis aims at investigating the Al/CFRP stack drilling process considering the differences in terms of behaviour between the two materials under different cutting conditions.

With the aim to examine in more details the characteristics of thrust force and torque pertaining to Al drilling and those pertaining to CFRP drilling, a further sub-segmentation procedure was also applied to the sensor signals.

To distinguish the drilling phases related to Al and CFRP, respectively, a smoothing filter was applied to the acquired thrust force signals, allowing to clearly point out the Al sheet drilling phase and the CFRP laminate drilling phase (Fig. 2). From the figure, two distinct portions can be identified on the thrust force signal, the first one related to Al drilling (signal segment on the left of the blue line in Fig. 2) and the second one related to CFRP drilling (signal segment on the right of the blue line in Fig. 2).

Hence, by separately considering these two portions as well as the whole signal in the following signal processing and feature extraction phase, the set of sensor signal features is expanded and more useful information can be detected.

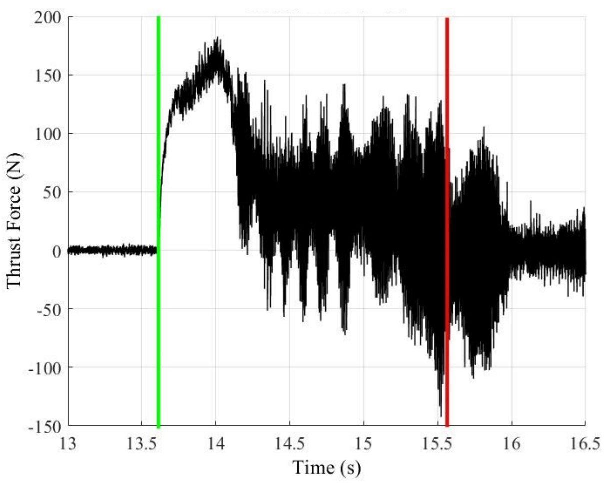

Fig. 2. Segmentation of the thrust force signal.

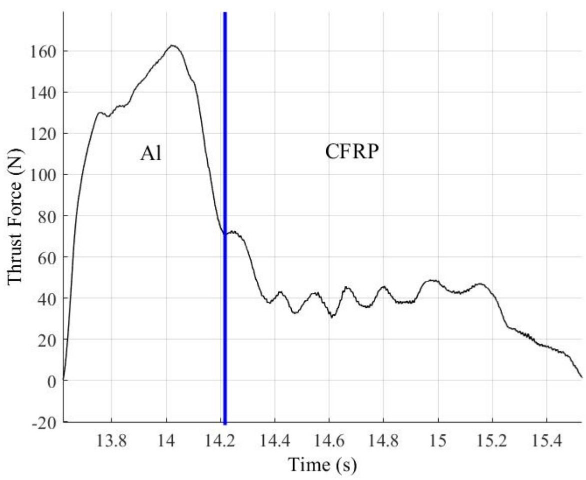

Fig. 3. Segmented and filtered thrust force signal.

3.1. Analysis in the time domain

Signal analysis in the time domain was carried out with the aim to extract statistical features characterising the thrust force and torque signals. The analysis was carried out on the whole smooth signal (including Al and CFRP), the sole Al signal segment and the sole CFRP signal segment. For each one, the following four statistical features were extracted:

- Average
- Variance
- Skewness
- Kurtosis

Therefore, for each feature, the extraction procedure provided three values. The first one identifies the whole process and was generated from the analysis of the whole signal, the second one identifies drilling of the Al sheet, the last value identifies drilling of the CFRP laminate. The blue line, which identifies the separation between the two signal segments belonging to the different materials was identified on the thrust force sensor signals and confirmed through the calculation of the drilling time considering the thickness of the Al sheet, which was the first involved in the drilling process, and the feed rate (mm/min).

3.2. Analysis in the frequency domain

With the aim to take into account the frequency-related information which was neglected by the initial sensor signal analysis in the time domain, a methodology for peak analysis in the frequency domain was applied.

As a matter of fact, the thrust force and torque signals acquired during Al/CFRP stack drilling show high frequency oscillations (Fig. 2). This phenomenon is particularly accentuated the CFRP portion, where high amplitude oscillations are observed due to the anisotropy of the CFRP laminates, which display greater mechanical properties along the fiber directions [13–15].

Based on the angle established between the cutting edge and the carbon fibers, i.e. the fiber cutting angle, different cutting modes occur [16]. During the revolution of the drill bit, the fiber cutting angle varies and affects the interaction mechanism between the tool and the work material, generating the high amplitude oscillations observed in the sensor signals [17].

Moreover, in multidirectional CFRP laminates, different cutting modes also take place at the same time along the cutting edge, due to the different fiber orientations of the several plies concurrently cut by the drill bit.

With the aim to investigate such complex frequency content of the thrust force and torque sensor signals acquired during the Al/CFRP drilling tests, advanced signal analysis and feature extraction was carried out in the frequency domain. Also in this case, the analysis was carried out on the whole signal (including Al and CFRP), the sole Al signal segment and the sole CFRP signal segment.

The Fast Fourier Transform (FFT) algorithm, implemented through the MATLAB fft function, was applied to convert the acquired signals of force and torque to the frequency domain.

Fig. 4 shows the FFT of the whole thrust force signals acquired during the experimental Al/CFRP stack drilling tests performed at 3000 rpm and 0.15 mm/rev (the revolution frequency in this case is equal to 3000 rpm/ 60 = 50 Hz).

As observed in Fig. 4, significant peaks were detected at 1x, 2x, 3x, 4x, 5x, 6x, and 8x the revolution frequency.

This behavior seems to confirm the strong relationship between the signals frequency peaks and the influence of the cutting angle varying in the drilling process according to the diverse fiber orientations in the multidirectional laminates.

To further analyze the behavior of these frequency peaks, the evolution of the amplitudes of the peaks with increasing number of holes was investigated.

From a first visual examination, the amplitude of some of the peaks shows an increase with increasing number of holes. This suggests a potential correlation of the peak amplitude with tool wear progression. A statistical procedure was implemented for the selection of the most relevant features among those extracted in the frequency domain.

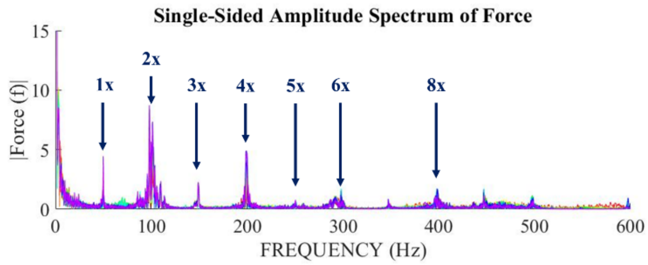

Fig. 4. FFT of the thrust force signals acquired in drilling tests at 3000 rpm, 0.15 mm/rev.

4. Results and discussion

The features extracted in the time domain as well as those extracted in the frequency domain were further analysed to verify their potential correlation with tool wear progression.

To this aim, a statistical procedure based on the calculation of the Spearman's correlation coefficient, r_s, was applied. In this way, the correlation between each extracted feature and the corresponding tool wear value was quantitatively evaluated.

Table 2 shows the list of the most correlated sensor signal features and the corresponding value of the Spearman's correlation coefficient, r_s. As it can be observed, several features showed a strong correlation with the measured tool wear values ($r_s > 0.7$). Moreover, it is interesting to notice that both the sensor signal features provided by statistical analysis in the time domain and those provided by peak analysis in the frequency domain are strongly correlated with tool wear.

It is also worth mentioning that, in Table 2, it is possible to observe the presence of features extracted from the whole signal as well as those extracted by considering the sole Al segment and CFRP segment separately.

The validity of the Al and CFRP segment separation approach is shown in Table 3 which reports the values of the Spearman's correlation coefficient calculated for the Torque Average of the whole signal, of the Al segment and of the CFRP segment. The values reported in the fourth column, which refers to the torque average of the CFRP segment, are considerably higher than the values reported in the third column which refers to the torque average of the Al portion.

In some cases, the correlation values of the CFRP segment are even higher than the correlation values of the whole signal. This behaviour can be easily shown via graphical analysis of the thrust force variance.

Fig. 5 reports the development of the thrust force variance with increasing number of holes for the whole signal, the Al segment and the CFRP segment, for the experimental drilling tests carried out at 3000 rpm and 0.15 mm/rev. The thrust force variance values for the whole signal (red circles) appear to be very scattered. On the other hand, the thrust force variance development for the Al segment (blue squares) appears to be better correlated with the tool wear development. Finally, the thrust force variance development for the CFRP segment (green triangles) shows the highest correlation with tool wear progression compared to the two previous graphs.

Table 2. List of the most correlated features and corresponding r_s value.

Feature	Spearman coefficient value, r_s
Fz_{avCFRP}	0.97
Fz_{av}	0.97
Fz_{avAl}	0.95
Fz_{varAl}	0.94
Fz_{avCFRP}	0.93
Fz_{peak2x}	0.92
$Fz_{peak2xCFRP}$	0.91
T_{avCFRP}	0.85
T_{av}	0.82
Fz_{peak4x}	0.77
$Fz_{peak4xCFRP}$	0.77

Table 3. Spearman's correlation coefficient values for the torque average.

Process Parameters	Torque Average (Al + CFRP)	Torque Average Al	Torque Average CFRP
3000 rpm – 0,05 mm/rev	0.91	0.69	0.92
3000 rpm – 0,10 mm/rev	0.87	0.69	0.89
3000 rpm – 0,15 mm/rev	0.97	0.69	0.82
4500 rpm – 0,05 mm/rev	0.77	0.64	0.80
4500 rpm – 0,10 mm/rev	0.62	0.18	0.80
4500 rpm – 0,15 mm/rev	0.64	-0.18	0.79
6000 rpm – 0,05 mm/rev	-0.26	-0.18	-0.25

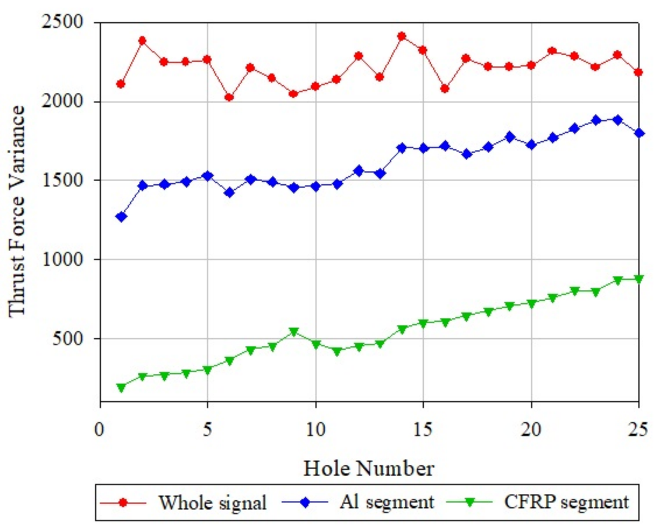

Fig. 5. Thrust force variance 3000 rpm 0.15 mm/rev.

Table 4. Spearman correlation coefficient values.

Frequency features	3000 rpm – 0,05 mm/rev (Al + CFRP)	3000 rpm – 0,05 mm/rev (Al)	3000 rpm – 0,05 mm/rev (CFRP)
Thrust Force peaks 1x	-0.45	-0.46	-0.40
Thrust Force peaks 2x	0.90	0.44	0.91
Thrust Force peaks 3x	0.70	-0.36	0.66
Thrust Force peaks 4x	0.90	0.67	0.90
Thrust Force peaks 6x	0.70	0.41	0.72
Thrust Force peaks 8x	0.86	-0.04	0.86
Torque peaks 6x	0.64	0.77	0.65

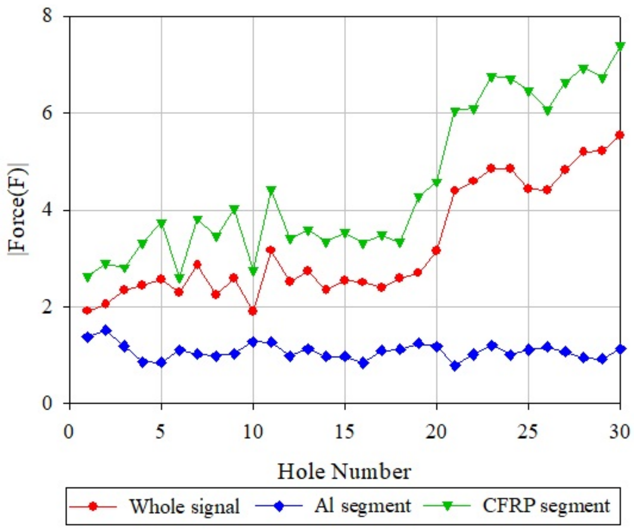

Fig. 6. Frequency peaks analysis Thrust force 4x 3000 rpm 0.15 mm/rev.

A similar behaviour was reported from peak analysis in the frequency domain. Table 4 shows the Spearman's correlation coefficient values calculated by analysing the whole signal and the Al and CFRP segments.

Also in this case, it is possible to notice a significant increase in the correlation values obtained by analysing the Al and CFRP segments separately.

In particular, the highest correlation values were obtained on the CFRP segment which is the most dominant signal portion with reference to the frequency content because it is very sensitive to the presence of the reinforcing carbon fibres with different orientations, as explained in section 3.2.

Differently from the previous case shown in the time domain, the CFRP segment shows to have a greater influence on the analysis of the whole signal in the frequency domain. Fig. 6 shows the amplitude of the frequency peaks of the thrust force at 4x the revolution frequency for the experimental tests carried out at 3000 rpm and 0.15 mm/rev. As it can be observed, the red line shown in Fig. 6, which is relative to the whole signal, is very similar to the green curve, which is relative to the CFRP segment, showing a growing trend with increasing number of holes and hence with tool wear progression.

Contrariwise, the blue curve, which represent the Al segment, does not show any trend with increasing number of holes, because the frequency content of the Al signal segment is less significant than that of the CFRP segment.

5. Conclusions

Drilling of hybrid Al/CFRP stacks poses several challenges due to the diverse machining properties of two distinct materials, that require different optimal machining conditions. In order to monitor the process behaviour and to create the basis for a future process monitoring system architecture based on cognitive paradigm, a multiple sensor monitoring procedure based on the acquisition of thrust force and torque signals was developed with the aim to investigate the correlation between the sensor signal features and the tool wear.

It was reported that high feed (0,10 mm/rev and 0,15 mm/rev) and high spindle speed values are not suitable for the drilling of Al-CFRP stacks: as a matter of fact, the tests with spindle speed equal to 6000 rpm and feed 0,10 mm/rev and 0,15 mm/rev were early stopped due to tool breakage.

In accordance with literature, the increase of the spindle speed makes the process conditions more severe for this stack configuration. At the same time, also the correlation coefficient values decrease and it becomes more difficult to find correlation coefficients which show moderate and strong correlation, it leads to difficulties in monitoring the process through sensor signal analysis. This is due to the effect of the fibre cutting which negatively influences the sensor signal monitoring of the thrust force and torque.

Sensor signal analysis was performed in the time and in the frequency domain allowing to obtain features of different nature able to better characterize the sensor signals. Moreover, the separation between the Al signal segment and the CFRP signal segment was performed. Despite the more efforts required to extract a higher number of features, this methodology proved to be valuable for process monitoring with particular reference to tool wear conditions. As a matter of fact, in many cases the features displayed a higher correlation with tool wear when extracted considering the single Al or CFRP signal segment instead of the whole signal.

Considering the entire experimental plan, it was reported that using moderate spindle speed (3000 and 4500 rpm) and medium feed 0.10 and 0.15 mm/rev the best results in terms of sensor signals correlation were obtained.

This is due to the trade-off conditions with spindle speed sufficiently high to meet the required Al drilling conditions and sufficiently low to avoid the negative effects that arise in CFRP drilling due to the abrasive fibres which produce very fast tool wear at high spindle speed.

As regards the feed, these values are sufficiently high to reduce the distance travelled by the cutting edge along its spiral path down through the hole, thus reducing wear rate in CFRP drilling, and sufficiently low to avoid tool breakage during aluminium drilling [8].

Further experimental drilling tests should be performed to investigate the process behaviour under different cutting conditions, in particular considering an increase in the feed with the objective to further improve the productivity of the hybrid stacks drilling process.

The results reported in the previous paragraph, in terms of correlation coefficient values and number of selected features show that the multiple sensor monitoring procedure can be usefully employed to feed a cognitive-based paradigm system for on-line tool condition monitoring.

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