Characterising Conveyor Belt System Usage from Drive Motor Power Consumption and Rotational Speed: A Feasibility Study

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ABSTRACT

Conveyor belt systems constitute a fundamental means of transferring bulk materials throughout industry. Typically, systems are subjected to very high levels of utilisation and, because of their criticality to process flow, high reliability is demanded. Currently preventative approaches to the maintenance of systems are implemented in the majority of applications, in which time-based intervention intervals are applied. The effectiveness of time-based intervals can be limited, as their premise is based upon an assumption that system condition is solely a function of operating time. In practice degradation of systems is primarily a function of usage, affected by intensity as well as duration of operation. Consequentially, this paper aims to investigate the feasibility of inferring the usage of a conveyor belt system from observation of drive motor electrical power consumption and speed responses, to support improvements in maintenance effectiveness.

First, an industrial conveyor belt system is instrumented, and a range of test scenarios are designed such that the response of parameters to various usage patterns can be characterised. Through inspection of these responses it is found that the parameters monitored do show sensitivity to changes in operational conditions such as utilisation, inclination and loading events, and it is therefore feasible to infer conveyor belt system usage from motor power consumption and speed only. Next, a series of proxies for describing system usage are then proposed, as a means of transforming raw parameters into usage profiles. Finally, the technical challenges facing industrial implementation of the proposed approach are discussed, and consideration given to how usage information may provide value to operators outside of maintenance.

1. INTRODUCTION

Conveyor belt systems (CBS) are a fundamental class of asset within bulk handling industries, which provide materials transfer functionality within processes spanning all stages of a material's life, from initial extraction through to end-of-life disposal or reuse. Throughout its service life an industrial conveyor belt system will be subjected to demanding and varying operational conditions, whilst being expected to meet stringent reliability requirements. Additionally, in flow-based operations such as those within the bulk handling industries, an individual conveyor system will often represent a single-point-of-failure within the overall process. As a result, maintenance of systems plays a critical role in supporting operations, with operators continuously seeking improvements in the effectiveness of maintenance regimes.

1.1. Maintenance of Conveyor Belt Systems

Presently, conveyor systems are predominantly maintained via preventative regimes, in which maintenance interventions are made either at fixed, time-based intervals or when the condition of the asset is deemed to have degraded to an unacceptable level. Within such approaches the determination of asset condition is a manual task conducted by maintenance personnel, primarily utilising visual inspection of assets. Using visual inspection to assess the condition of assets can be problematic for operators; not only does it rely upon the availability of experienced personnel, leaving operators vulnerable to personnel churn, it also introduces a significant degree of subjectivity into assessments. By its nature, visual inspection also requires operators to have physical access to plant in order to conduct inspections, which is not necessarily possible, either due to safety concerns or due to remote operation of systems (Freeman Gebler, Hicks, Harrison, Barker, & Stirling, 2016).

Therefore, while historically such regimes were deemed sufficient to support operations, the impact on overall maintenance effectiveness resulting from inaccurate assessment of asset conditions is increasingly considered to be unacceptable by operators. Whilst some maintenance interventions will be required periodically, and others at ostensibly random intervals, the majority will be required as a function of the system's usage, as noted by Tinga (2010).

In this context the term usage is used to describe the work done by a conveyor system, reflecting not only total work done but also the form and sequence of that work, and is thus influenced by dynamic events as well as steady-state operation. Usage is a relative measure dictated by the designed limits of a specific system, which define overload and abuse conditions. An overload condition is defined as one in which normal operating limits are exceeded but not safety factors, whereas an abuse condition is one in which safety factors are exceeded and thus the system is operating beyond its 'designed for' limits, potentially compromising system integrity. It should be noted that there is a distinction between the operation and usage of a system; two systems could be operated for identical periods of time but have vastly different usage.

Consequently, it is proposed that providing operators and OEMs with usage information to supplement or replace existing visual inspection information may enable more appropriate maintenance intervals to be scheduled in comparison to existing approaches, so as to minimise unnecessary interventions and hence maximise the effectiveness of preventative maintenance actions.

1.2. Bulk Handling Industries Characterisation

In order to profile the usage of a system in-service continuous observation of how it is being operated is required. Currently, few applications of real-time monitoring of systems operation have been observed within the general bulk handling industries, restricted by a number of industry-specific issues, as summarised in Table 1.

Given such constraints, it can be asserted that for successful implementation of a usage profiling concept within the bulk handling industries any solution must be able to deliver tangible and measurable impact to operators, without incurring significant disruption to existing processes, within a cost-effective model.

Table 1. Issues facing the application of new technologies within the bulk handling industries

	Issue	Explanation
1	Access to 'state of the art' technologies	Historically the general bulk handling industries have not been engaged with the latest advances in technology, resulting in a somewhat 'agricultural' approach being employed. Equally, technology developers have neglected the industries, in favour of higher-profile industries such as aerospace, automotive and renewables.
2	Operational constraints	Due to extremely high levels of asset utilisation there is little opportunity for new technology implementation, particularly if implementation may disrupt day-to-day operations. Additionally, personnel resources are typically scarce and often significantly transient, meaning availability of experienced personnel to champion new technology is absent.
3	Financial viability	Despite facilitating overall processes of high value, conveyor assets within bulk handling industries are themselves relatively low in value, therefore, the implementation of a PHM solution, which may require both hardware and software requisitions, can be prohibitively expensive. Direct costs associated with maintenance actions (e.g. parts) are generally relatively insignificant, therefore unless a clear return-on-investment can be demonstrated through improvements in process availability/throughput, producing a viable financial proposal can be challenging.
4	Technical suitability	Assets are operated intensely and in harsh environments, therefore, new technology must be able to withstand such abuse, as well as account for the wide range of use-cases a single asset may be subjected to.

1.3. Usage Profiling of Conveyor Belt Systems

In order to quantify the usage of conveyor belt systems within the bulk handling industries whilst addressing these constraints an energy transfer-based approach to usage profiling is proposed, in which the energy into the system is used to infer the energy out i.e. the usage of the system. In this solution raw motor electrical power consumption and speed parameters are monitored to enable the energy into a system to be observed, from which a range of proxies are derived, which it is proposed will together reflect the usage of a conveyor belt system.

The proposed approach is based upon observing the response of motor electrical power consumption and rotation speed parameters alone for three primary reasons:

- Sensitivity to load – In order to capture the usage of a system monitored parameters should be sensitive to torsional loading events associated with the kinetic energy required to convey material along the belt. The electrical power consumed by an induction motor is inherently related to the torsional load applied to the motor and its rotational speed, and examples of utilisation of these parameters to observe energy consumption and motor health are widely reported in literature, typically under the banner of motor current signature analysis (e.g. Benbouzid, 2000; Lu, Habetler, & Harley, 2008).
- Non-intrusiveness – Power and speed parameters can be monitored in a non-intrusive manner, as they do not require mechanical fastening directly onto the motor as required to monitor temperature or vibration, for example, which both reduces installation effort as well as increasing the reliability of monitoring.
- Low cost – The hardware and technology required to monitor power consumption and speed parameters is well established, and they can thus be observed using relatively inexpensive hardware, compared to acoustic emission or vibration parameters, for example. In fact, many variable frequency drive (VFD) based systems make such parameters available to the operator already.

Correspondingly, the aim of this paper is to investigate the sensitivity of motor power consumption and speed parameters to changes in system usage, and thus assess the feasibility of the proposed approach to profiling the inferring the usage of a conveyor belt system. from observations of changes in drive motor electrical power consumption and conveyor speed. This is achieved through the conducting of a series of conveyor characterisation tests (CCTs), based around the operation of an instrumented industrial conveyor belt system. First, a data acquisition system is developed in order to enable observation of motor power consumption and speed parameters, and a range of test scenarios are then developed, such that the system is operated over its complete design envelope, enabling comprehensive characterisation of monitored parameter responses. Scenarios implemented include changes in both system loading as well as the physical configuration of the system.

Through inspection of test scenario data it is shown that relationships do exist between system usage and parameter responses, and thus discriminating between different usage scenarios using only motor power consumption and speed parameters is feasible. The paper concludes with a discussion of how raw acquired data could be transformed into a system usage profile based upon a proposed series of derived proxies for usage, as a means of supplementing existing preventative maintenance regimes, as well as to support system design/redesign activities. Finally, a summary of the technical challenges necessary to automate the proposed approach is presented

2. EXPERIMENTAL METHODOLOGY

To characterise the response of motor power consumption and speed parameters to changes in usage a series of test scenarios were designed and conducted, based around the operation of an instrumented industrial conveyor belt system.

2.1. Subject Conveyor

All tests were conducted on a single conveyor belt system, provided on loan from the manufacturer in an ‘as new’ condition with no wear. The system provided for testing was configured with a chevron belt pattern and belt width of 450mm, and an overall conveyor length of approximately 3m (Figure 1).

The belt is driven by a single-phase induction motor with a rated output power of 2.2kW, via a 15:1 reduction gearbox, both located at the head pulley end of the system. The drive motor is a 4-pole machine, with a synchronous speed of 1500rpm, and a nominal operating speed of 1350rpm when supplied by a 50Hz AC waveform. Power to the system is provided from a mains supply, via a 110V step-down, isolating transformer, with the drive motor being controlled manually via a direct-on-line (DoL) starter box.

2.2. Data Acquisition

During the completion of CCTs a range of electrical power and rotational speed parameters were continuously monitored, as shown in Table 2. Motor power parameters were acquired via direct connections to the motor power supply lines, fed into a LEM NORMA 4000 power analyser. Synchronised samples of power quantities were acquired approximately every 20ms (50Hz), where each sample reflected the root-mean-square (RMS) value of that parameter during the previous 20ms period. A 20ms interval was the minimum possible using the LEM NORMAs 4000 unit.

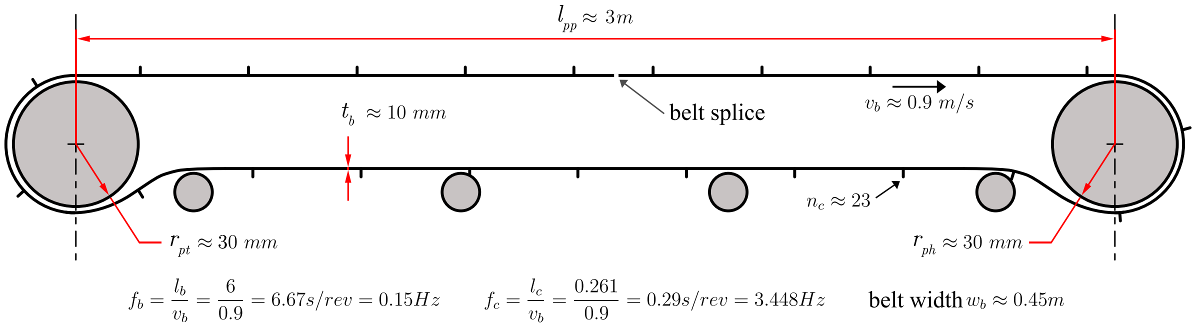

Figure 1. Geometry of subject conveyor belt system

Data samples were acquired by the unit and stored locally, from where they were bulk transferred to the local control PC every 30s. It should be noted that during the transfer period (200ms) the power analyser was unable to simultaneously acquire further samples, hence every 30s a discontinuity of ~200ms can be observed in each acquired power data set.

The rotational speed of the gearbox output shaft was monitored directly using a Honeywell SR3C-A1 non-contact, Hall effect sensor, in conjunction with a bespoke magnet wheel. In addition to the parameters presented in Table 2 during the conducting of each test scenario video was recorded, to enable subsequent validation of the loads applied during each test.

Table 2. Parameters monitored during CCTs

Component	Parameter	Units	Sample Rate
Motor	Line Voltage	Vrms	~50Hz
Motor	Current Draw	Arms	~50Hz
Motor	Active Power	Wrms	~50Hz
Motor	Apparent Power	VArms	~50Hz
Motor	Reactive	VARrms	~50Hz
Motor	Power Factor	-	~50Hz
Gearbox	Output Speed	RPM	Count
Belt	Linear Speed	ms^{-1}	Count

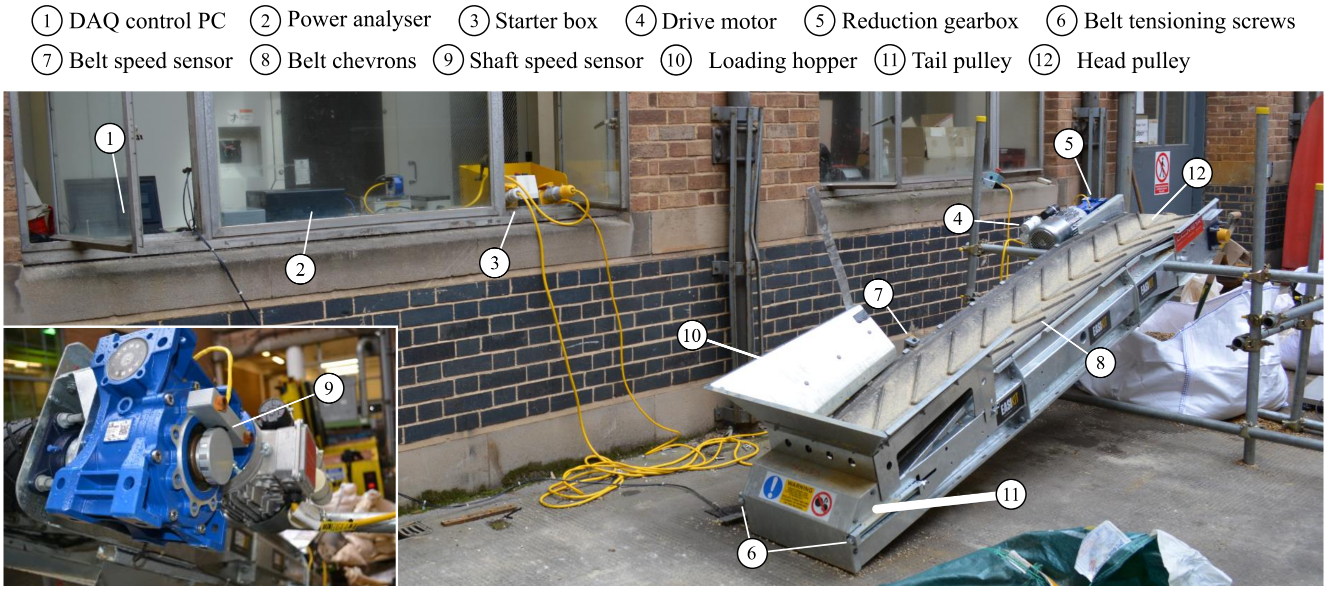

Figure 2. Overview of conveyor characterisation testing setup

2.3. Test Scenarios

A series of test scenarios were designed to investigate the sensitivity of monitored conveyor belt system parameters to changes in operational conditions. Each series of test scenarios involved a single operational parameter being varied, such that, in its entirety, the testing programme would represent a comprehensive set of conditions which the system could be expected to experience throughout its service life, based upon the manufacturer's system specification.
Each test scenario group was given an ID of the format CCT.X where X was a unique character, as presented in Table 3.

Loading was applied to the conveyor as required using masses of various denominations, to reflect a range of typical applications, up to a maximum of 30kg, as stipulated by the manufacturer. All masses were composed of 'pea' gravel, approximately 10mm in particle size, contained within heavy-duty, woven sacks, which were manually loaded onto the system at a rate and height as required for each test scenario.

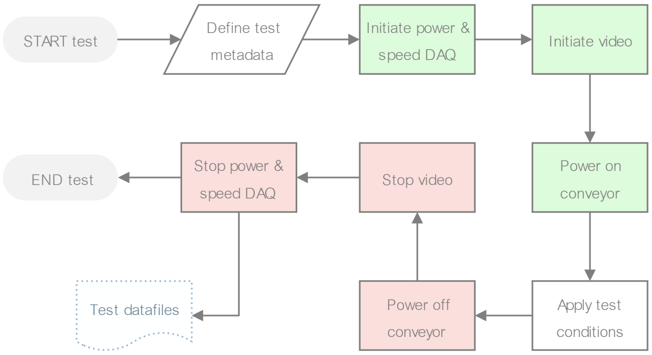

Figure 3. Outline of procedure followed during the completion of test scenarios

During each test scenario a strict procedure was adhered to, ensuring tests were completed safely, as well as consistently, the major steps of which are illustrated in Figure 3.

Table 3. Summary of CCT scenarios conducted

Test Group ID	Test Scenario	Test Variables: Conv. Incline (°)	Load Masses (kg)	Load Height (m)	Loading Freq (s)	Belt Tension (turns)	Implementation Details
CCT.A	Idling conveyor baseline	0, 15 30	None	N/A	N/A	0	No additional masses loaded onto conveyor during baseline tests.
CCT.B	Varying angles of incline	0 15 30	loose 1 10 20 30	0	2	0	A maximum of 30° of incline was investigated due to health and safety limitations, as well as performance limitations associated with a chevroned belt.
CCT.C	Varying product composition	0	loose 1 5 10 20 30	0	1 2 3	0	Masses were manually loaded onto the system, therefore nominal loading frequencies were adhered to as closely as possible however, limited accuracy in practice.
CCT.D	Varying loading heights	0	loose 1 5 10 20 30	0 0.3 0.6	2	0	Masses were dropped from heights as close as possible to the nominal height, using a measurement stick for reference, however some variability induced.
CCT.E	Varying magnitudes of belt tension	0	10	0	2	+1,2,3,4,5 -1,2,3,4,5	Belt tension adjusted by tightening or loosening both tensioning nuts evenly by the number of turns required.

3. RESULTS

For each series of test scenarios conducted only a subset of monitored parameter responses is presented for reasons of brevity. To illustrate the general response of monitored parameters both time-domain gearbox output speed and time- and frequency-domain motor apparent power consumption parameters are shown. Apparent power values plotted represent either the absolute root-mean-square (RMS) value of the previous 20ms period, or the RMS level relative to the idling RMS level, to remove steady state effects. Each frequency spectra presented corresponds to a test specific time period, as indicated in each figure, and are Hamming windowed to reduce spectral leakage. For tests in which masses are loaded onto the belt results from the maximum denomination of mass loaded (30kg) are shown as effects are typically most obvious.

3.1. CCT.A: Idling Characterisation

CCT.A scenarios involved conducting a long duration test (~10mins) at each inclination, with no load applied to the belt, to provide a baseline of normal, unloaded operation.

Time-domain data from CCT.A tests shows no significant longer-term effects to be present in either power or speed data (Figure 4). A slightly different steady state idling power consumption and speed can be seen across inclines, this is most likely a consequence of the order of completion of tests. All tests at each incline were completed consecutively, thus, CCT.E tests requiring a change in belt tension were conducted between starting and completing all CCT.A tests. Efforts were made to ensure that the belt tension was returned to a consistent tension for subsequent tests, however, in practice this couldn't be guaranteed.

Frequency-domain data shows no significant changes can be observed between tests, with the most prominent components in each spectrum correlating (Figure 4). Additional significant peaks are present at the belt passing frequency (0.15Hz) and its harmonics.

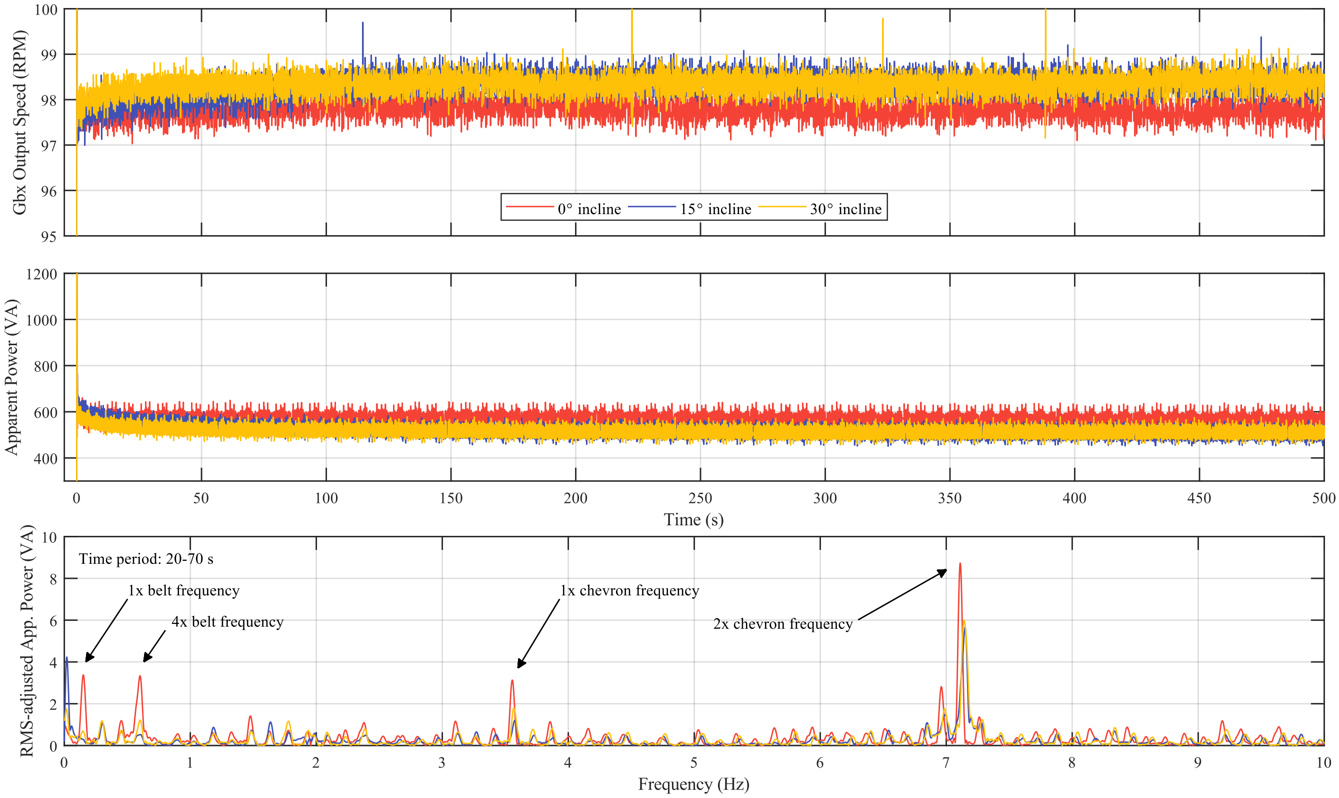

Figure 4. CCT.A: Idling characterisation time and frequency domain data

3.2. CCT.B: Inclination Characterisation

CCT.B scenarios involved varying the angle of conveyor inclination, with inclines of 0°, 15° and 30° investigated.

In CCT.B time-domain data a discrete spike in power consumption can be observed in response to each mass being loaded onto the belt (Figure 5). The magnitude of the spike induced appears to be unaffected by the conveyor angle of inclination; as seen in Figure 6, when differences in idling consumption are accounted for, the mean magnitude of spikes induced by 30kg masses does not increase as the conveyor's inclination is increased, with mean amplitudes of 220.2VA, 316.2VA and 214.1VA above RMS idling consumption observed for 0°, 15° and 30° inclination respectively.

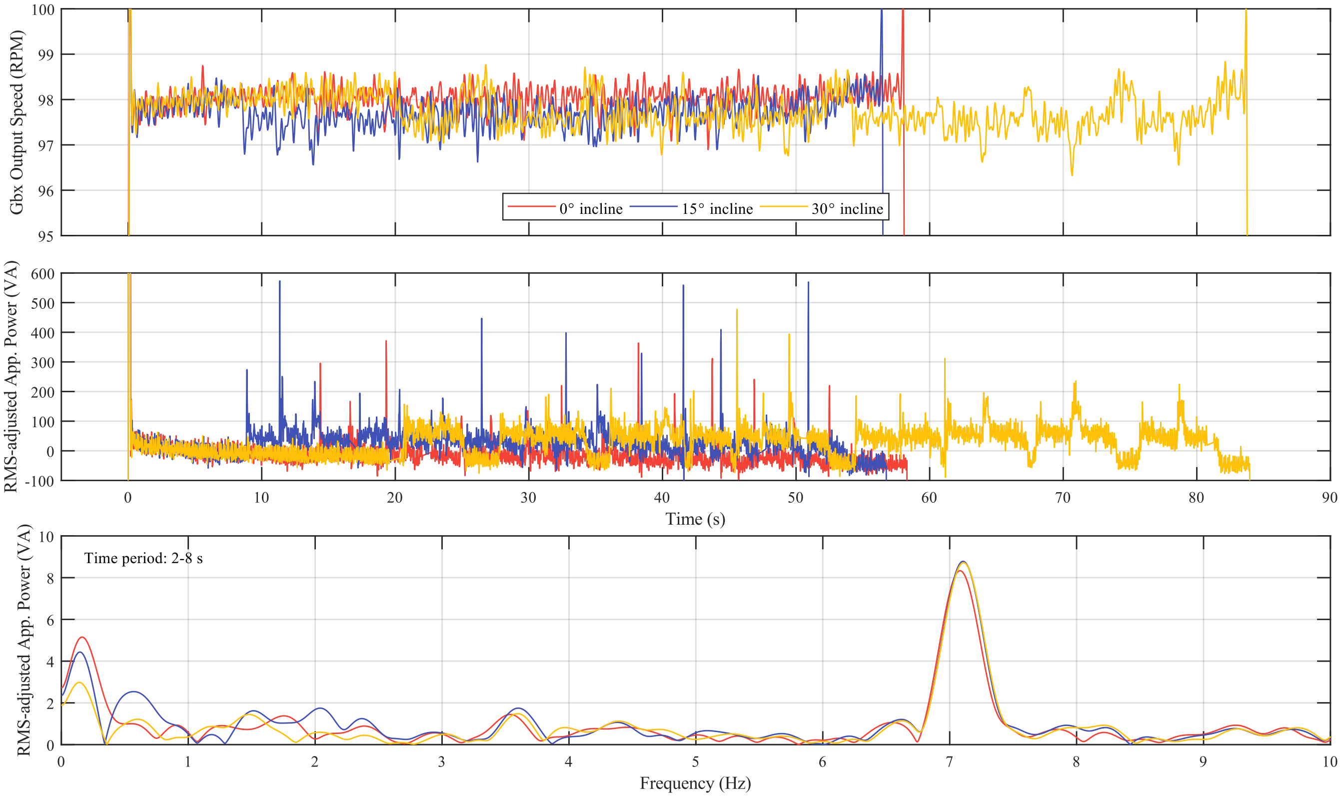

Figure 5. CCT.B: Conveyor inclination characterisation time and frequency domain data

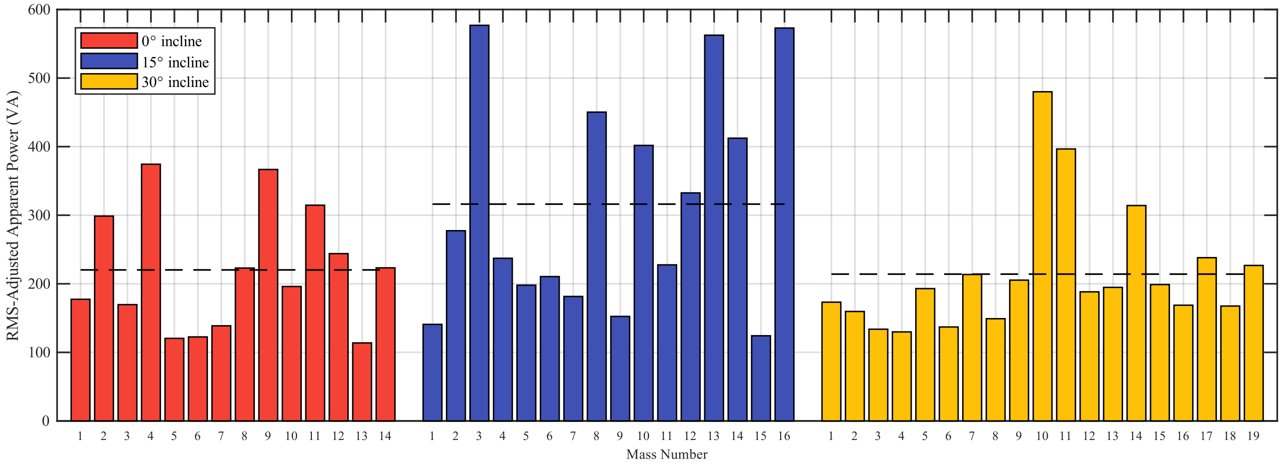

Figure 6. Magnitude of start-up transients induced in motor power consumption as a function of conveyor inclination

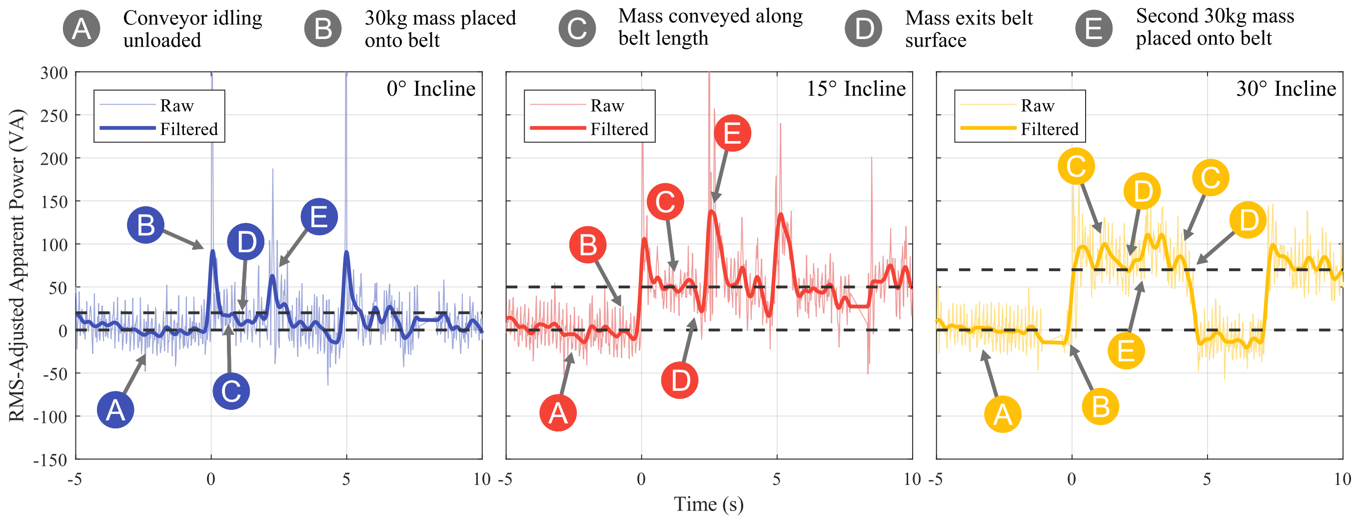

Figure 7. Magnitude of power consumed whilst conveying mass as a function of conveyor inclination

Such an observation is consistent with the mechanics of the system; the power consumption associated with the spike induced in response to a loaded mass represents the energy required to accelerate the stationary mass up to the nominal belt speed and is thus independent of the conveyor inclination.

However, during the period between the end of the loading spike and the mass exiting the end of the conveyor, the RMS power consumption of the motor can be seen to increase with conveyor inclination. This behaviour is highlighted in Figure 7, and corresponds to the period C.

It can be seen from Figure 7 how during period C within each test scenario the RMS power consumption is around ~25VA greater than idling at 0° inclination, ~50VA greater at 15° inclination and ~70VA greater at 30° inclination. Once each mass has exited the end of the conveyor (period D) and thus the belt is unloaded, the power consumption of the conveyor can be seen to return to its idling RMS consumption level.

Again, such observations can be explained from the mechanics of the system; as the conveyor is adjusted from being flat to inclined it is required to convey the mass on the belt not only in a horizontal direction, but also raise it vertically. This action is opposed by the force of gravity acting on the mass, and thus more power must be consumed by the drive motor in order to perform this additional work.

3.3. CT.C: Product Composition Characterisation

CCT.C scenarios were concerned with identifying the effect of loading different quantities of mass at different frequencies on the power consumption and rotational speed of the drive motor. All CCT.C tests were conducted on a flat conveyor.

CCT.C time domain data (Figure 8) shows that as each discrete mass is loaded onto the conveyor surface a corresponding spike in motor power consumption can be observed, with the magnitude of the spike being a function of the quantity of mass loaded. This spike represents the energy required to accelerate the loaded mass up to the nominal belt speed, as indicated by the corresponding change in rotational speed as masses are loaded.

Across all CCT.C test scenarios the duration of each spike induced in response to the loading of a mass onto the belt appears to be consistent, with a duration of ~0.1-0.2s throughout all tests, suggesting the duration is independent of the amount of mass loaded (Figure 9).

During CCT.C tests the effect of varying the loading frequency of applied masses was also investigated. As the frequency at which mass are loaded onto the belt is increased, the period between masses reduces accordingly (Figure 10), however, even at the fastest loading frequency implemented during tests (~1s) it is still possible to identify the loading of each individual mass.

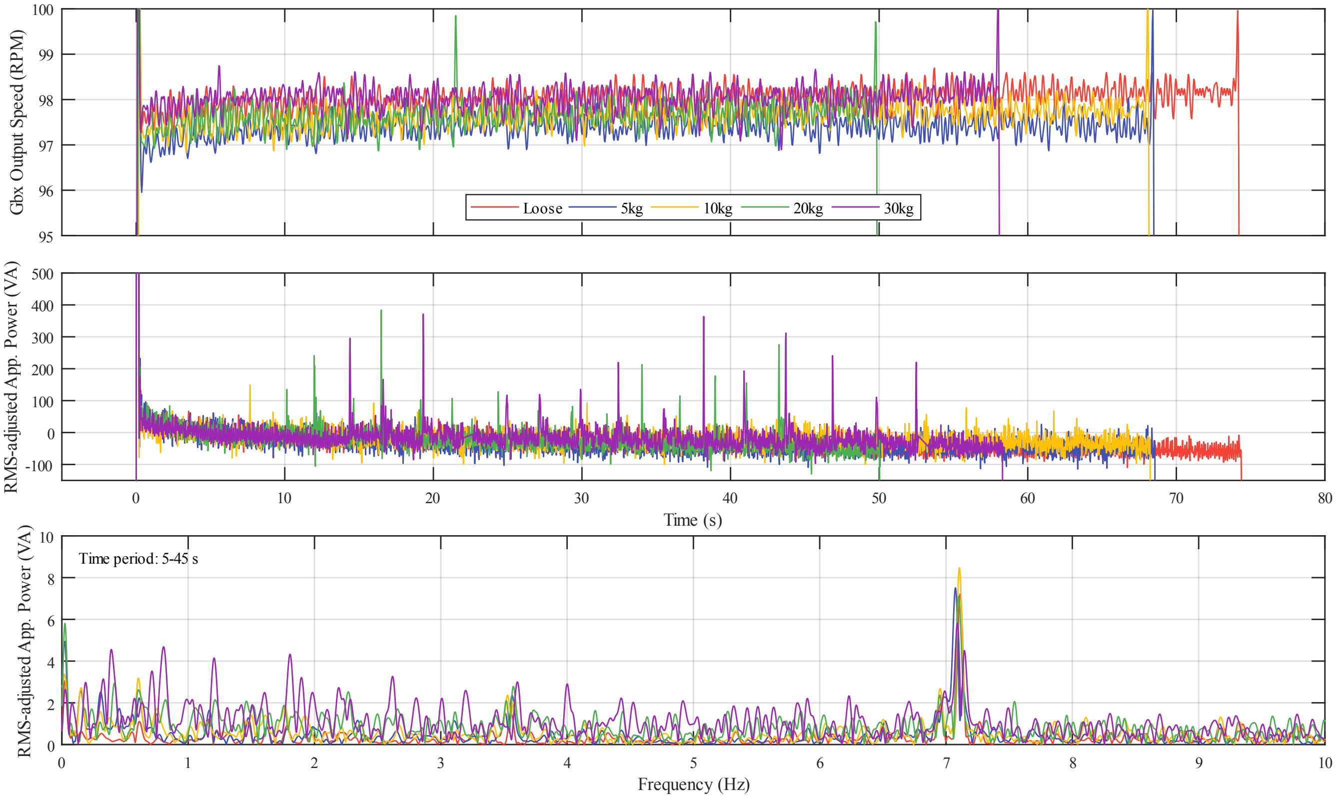

Figure 8. CCT.C: Product composition characterisation time and frequency domain data

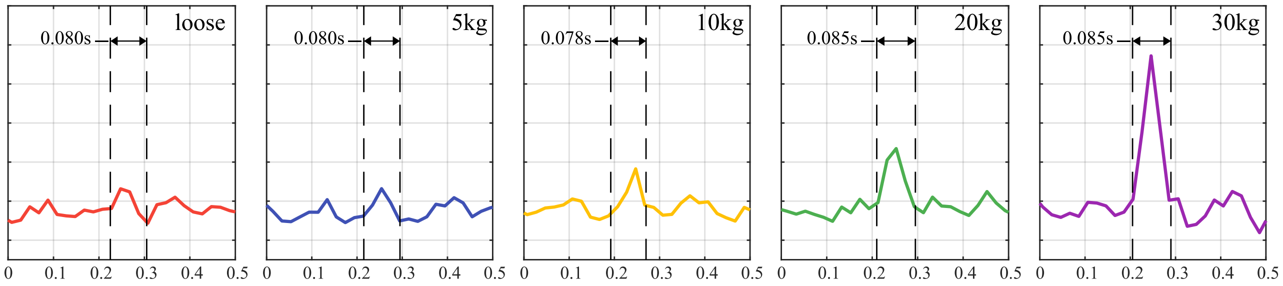

Figure 9. Duration of loaded mass-induced transients as a function of mass

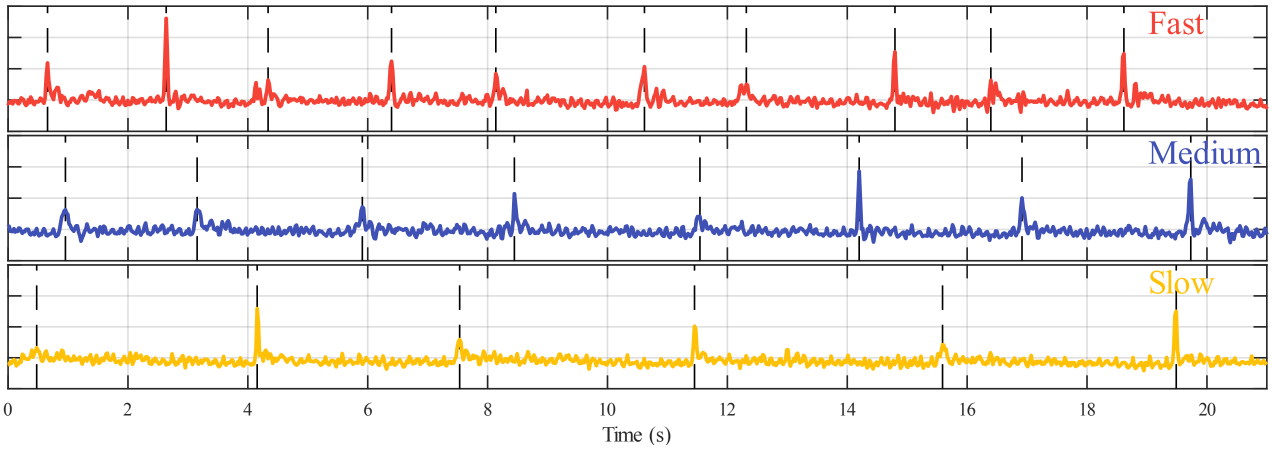

Figure 10. Loaded mass-induced transients as a function of loading frequency.

3.4. CCT.D: Loading Height Characterisation

CCT.D scenarios were conducted to investigate the effect of changing the mass loading height on the motor’s power consumption characteristics. Time-domain data from CCT.D tests shows that the magnitude of the spike induced by a mass being loaded onto the conveyor belt surface is directly related to the height from which it is dropped (Figure 11).

Increasing the height at which a mass is loaded from will increase the energy possessed by the mass, initially in potential form and subsequently in kinetic form. Thus, when the mass contacts the belt it applies a greater load to the drive motor, and so an increased consumption of power is observed as the motor attempts to maintain a constant speed. A transient decrease in belt speed can be observed initially, until the motor is able to accelerate back up to nominal operating speed, as demonstrated in the gearbox output speed plot within Figure 11.

Accordingly, in contrast to CCT.B test scenarios, the average magnitude of spikes induced by loaded masses does increase as the test variable, loading height, is increased (Figure 12).

Frequency-domain data from CCT.D tests indicate that as loading height is increased, an increase in the magnitude of broadband noise throughout the power spectrum is induced, which result in the analytical system frequencies previously identified being concealed. This is possibly caused by the action of the falling masses exciting natural frequencies associated with elements of the conveyor structure (Figure 11).

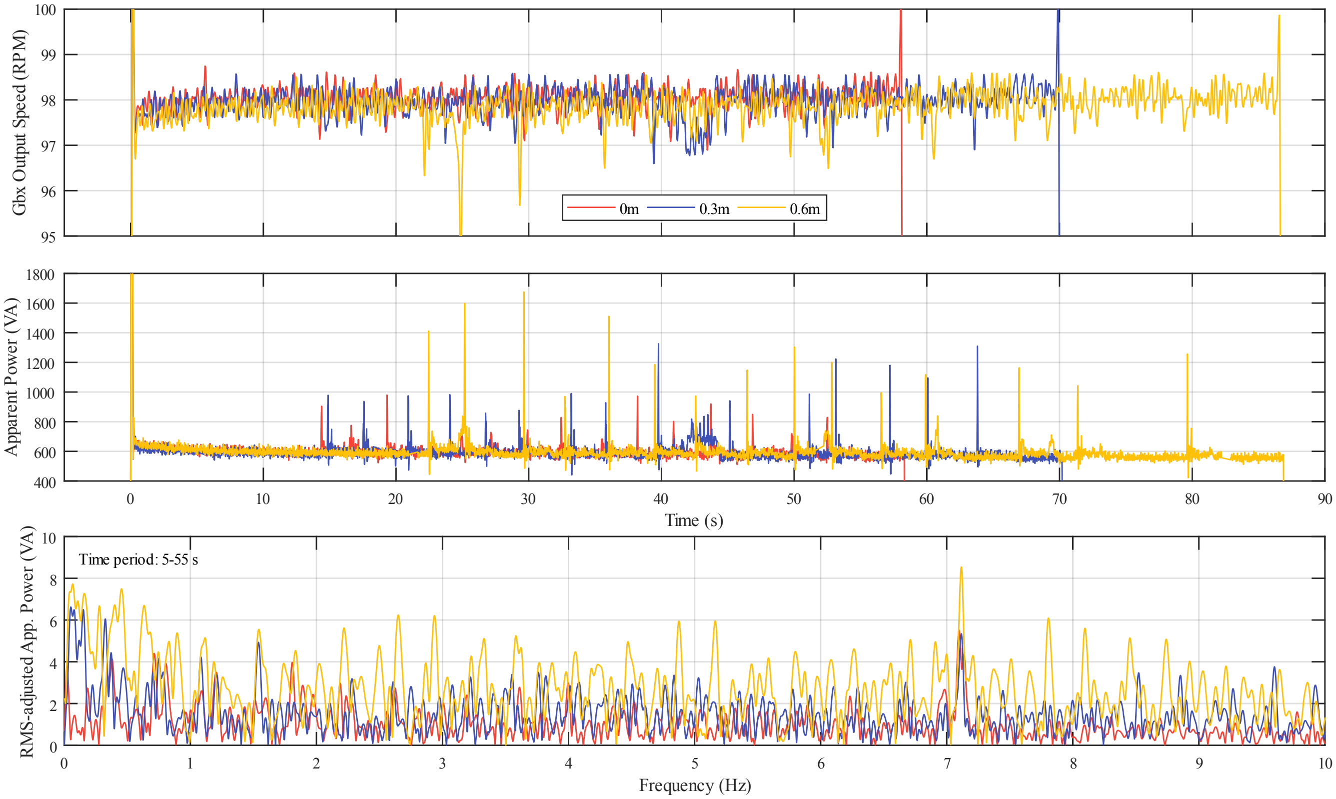

Figure 11. CCT.D: Loading height characterisation time and frequency domain data

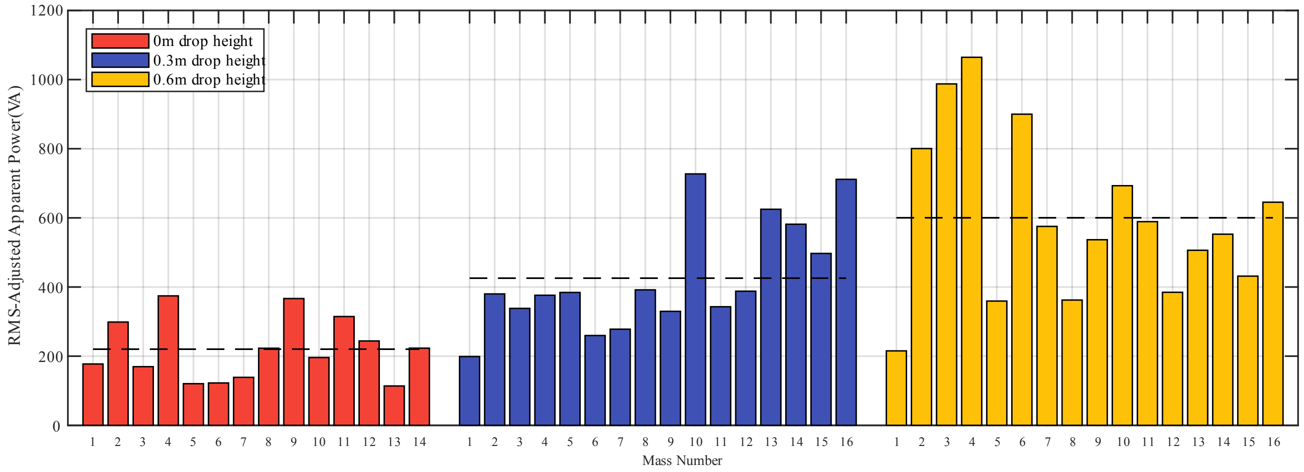

Figure 12. Magnitude of start-up transients induced in motor power consumption as a function of loading height

3.5. CCT.E: Belt Tension Characterisation

CCT.E scenarios involved both increasing and decreasing the longitudinal tension of the belt using the two adjustment screws at the tail end of the system to change the centre distance between the head and tail pulleys.

From Figure 13 the effect of changes in belt tension on idling power consumption can be observed, with consumption increasing as tension is increased, and decreasing as tension is decreased, varying by ~50VA in each direction from nominal idling consumption.

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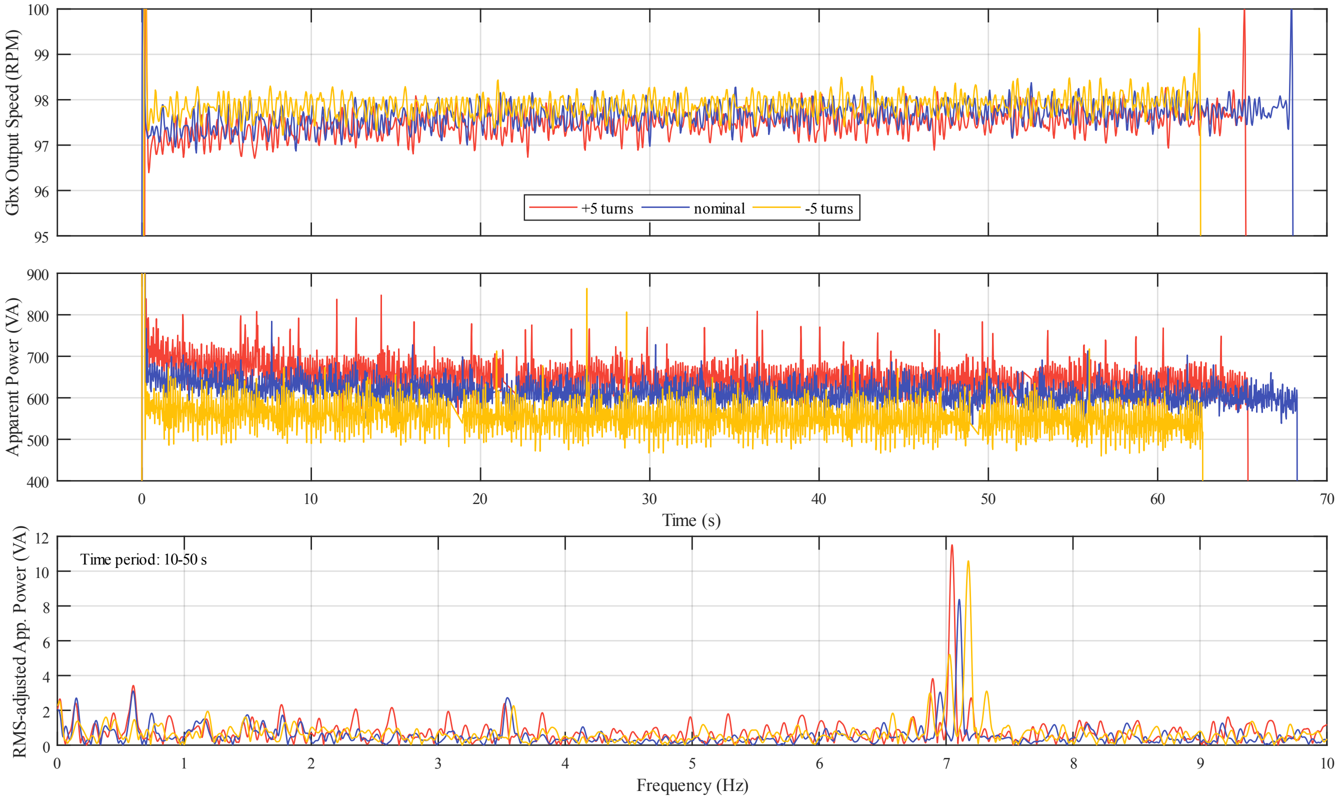

Figure 13. CCT.E: Belt tension characterisation time and frequency domain data

By increasing the centre distance of the pulleys, the total distance that the belt must travel to complete a revolution of the system is increased, and thus the belt must deform along its length to account for this. This elongation ca be observed within the frequency-domain spectrum of the motor power consumption, where the exact frequency of the chevron passing fundamental and first harmonic alters in response to changes in belt tension (Figure 13). This behaviour reflects the slight change in chevron spacing caused by the elastic deformation of the belt. When tension is increased the spacing of chevrons increases and so the frequency at which they pass is correspondingly decreased, due to the fixed speed operation of the drive system.

The gearbox output shaft speed can be seen to remain relatively constant as the tension in the belt, and thus idling power consumption, changes (Figure 13), with the drive motor maintaining an approximately constant speed under steady-state conditions as a result of its fixed frequency supply.

3.6. Summary of Results

Based upon the range of test scenarios conducted, a number of key findings have been made relating to the response characteristics of monitored parameters, as summarised in Table 4.

It can be seen that both motor power consumption and speed parameters are sensitive to mass loading, as well as to changes in the setup of the conveyor belt system. However, commonality in responses can be observed across different scenarios, potentially making differentiation between different types of event non-trivial. For example, the magnitude of transients induced by mass loaded onto the belt is affected likewise by both changing the quantity of mass loaded as well as the loading height.

Table 4. Summary of key findings from CCT scenarios

Test Group ID	Test Scenario	Observations
CCT.A	Idling conveyor baseline	- Transient peak ~5x idling RMS consumption is seen at every motor start-up, of ~100-200ms duration. - No obvious long-term temperature effects can be observed. - Components associated with belt and chevron passing frequencies clearly identifiable within apparent power consumption frequency spectrum.
CCT.B	Varying angles of incline	- Changing the conveyor's angle of inclination does not significantly affect the magnitude of the spike induced in response to a mass being loaded onto the belt. - RMS consumption whilst conveying a mass increases as the conveyor's angle of inclination is increased.
CCT.C	Varying product composition	- The introduction of a mass onto the surface of the belt will induce a transient increase in the power consumed by the motor. - While mass is being conveyed along the length of the belt the RMS power consumption of the system is increased compared to when idling. This increase is proportional to the quantity of mass loaded. - Discrete masses can be discerned even at 1s loading frequency.
CCT.D	Varying loading heights	- Transients induced by masses loaded onto the belt increase in magnitude as the height from which the masses are loaded increases. - Broadband noise is induced in data as mass loading height is increased, masking the analytical frequencies of the belt.
CCT.E	Varying magnitudes of belt tension	- Increasing the tension in the belt causes an increase in the power consumed by the drive motor when idling. - The characteristic frequencies associated with the belt are modulated compared to their analytical values. - No significant change in gearbox output speed observed as belt tension is adjusted.

4. USAGE PROFILING CONCEPT

Based upon the proposed approach to usage profiling of an industrial conveyor belt system as outlined in Section 1.3, an overview of the process through which raw, time-domain data collected from an industrial system can be transformed into usage profiles is described.

4.1. Proxies for Usage

To profile the usage of a specific conveyor belt system a range of different proxies are proposed, each of which represents either a cumulative or instantaneous measure of system usage.

As previously discussed, the concept of usage in the context of a conveyor belt system has no formal definition, therefore, proxies have been selected with the aim that they will provide a comprehensive characterisation of both duty and intensity demands. Proxies are selected both from relevant literature (Carnero, 2005; Jardine, Lin, & Banjevic, 2006; Larder, 1999), as well as first principles analysis of system behaviour.

Table 5. Summary of measures proposed for profiling system usage

	Proxy	Period	Description	Remarks
1	Running time	Cumulative	The total time a system has been operating for. This can be presented in a range of formats such as absolute time operating or average operating time between stops.	Does not describe how the running time is distributed, e.g. number of running periods, average period length etc., however, these could also be derived.
2	Number of start-ups	Cumulative	The total number of times a system has been started up from a stationary state under no load.	System health is likely to be affected negatively by increased exposure to the stresses of repeated acceleration and deceleration; therefore, capturing such events within usage is desirable.
3	Number of loaded start-ups	Cumulative	The total number of times a system has been started up from a stationary state under load.	The drive motor will experience increased load if the system is started from a condition where additional mass is present on the belt e.g. when restarting after an uncontrolled stop, which could result in damage to the motor.
4	Total travel	Cumulative	The total distance the belt has travelled.	For the subject conveyor, speed was constant, however, some systems will be variable speed.
5	Fluctuation in velocity	Moving window	The change in velocity of the motor between measurements.	Masses loaded onto the belt will cause deceleration of the system, therefore, by assessing the transient velocity response the loading of mass onto the belt may be able to be observed.
6	Work done	Cumulative	The cumulative power consumed by the drive motor.	Provides an indication of the total energy into the system, and thus throughput may be possible to infer.
7	Angular impulse	Cumulative	The cumulative change in angular momentum imparted by the drive motor i.e. the cumulative instantaneous torque generated by the motor.	Essentially combines the effects of fluctuations in power consumption and speed into a single measure.

8	Mass conveyed	Cumulative	The mass moved by the system via its belt. This can be presented in a range of formats such as total, average or masses which exceed design limits, for example.	Mass conveyed can be either discrete or continuous in nature, depending upon the material and application. Characterising the material conveyed provides value in a maintenance context.
9	Statistical moments	Moving window	The mean, variance, skewness and kurtosis values of motor power consumption during a specific period.	These values provide a means to characterise belt conditions within a specific period, via descriptions of the distribution of data, possibly enabling an inference of what is being conveyed.
10	Crest factor	Moving window	The ratio of the peak-to-RMS values of motor power consumption during a specific period.	Similarly to statistical moments, crest factor can be used to characterise the distribution of data during a period.

The proxies proposed here are derived from time-domain data in order to capture the transient nature of the observed responses in monitored parameters to loading events. Cumulative proxies are calculated based upon all data points captured in a measurement period, whereas moving window proxies are calculated from a segment of most recently captured data points, the length of which can be tuned to adjust the sensitivity of the proxy. Calculated proxy values can subsequently be broken down into periods of operation for interrogation, as appropriate, for example daily or weekly values.

4.2. Industrial Implementation

Within an industrial application of the proposed method of usage profiling, a number of challenges must be addressed in order to enable implementation at scale, when compared to the approach taken during the completion of CCTs. These include challenges associated with data acquisition, presentation and interpretation.

4.2.1. Data Acquisition

The approach to usage profiling as described is dependent upon the availability of accurate and complete motor power consumption and speed data. During the completion of CCTs a bespoke data acquisition setup was developed from commercial off-the-shelf parts and temporarily installed onto the subject conveyor. Such a setup was sufficient for the purposes of CCTs, however, it can be asserted that a number of issues associated with data acquisition hardware would have to be addressed prior to industrial implementation of the proposed approach.

Firstly, hardware must not be prohibitively expensive, both in terms of initial purchasing costs as well as ongoing costs (e.g. maintenance, data infrastructure etc.), in order for the system to adhere to the industry constraints described in section 1.2. Technology for monitoring the selected parameters is relatively mature and commonplace, therefore, it can be expected that an appropriately costed hardware solution is achievable. In fact, it is common for such parameters to be made available by modern motor control systems without modification.

Secondly, hardware must be robust enough to withstand the typical operational environments of the bulk handling industries. Conveyor belt systems, due to their functional generality, are typically subjected to aggressive environments, including extremes in temperature, humidity and mechanical vibration, thus, even though the selected parameters are able to be acquired in a non-intrusive manner any installed hardware must still be inherently robust to such conditions to avoid negatively impacting upon system availability.

Finally, any hardware must be system agnostic such that it can be installed onto diverse systems without significant modification. This includes being suitable for retro-installation, as well as designing into future systems.

4.2.2. Data Presentation

The proposed usage profiling concept must produce information which is able to be easily interpreted, to ensure that the future operation and maintenance of systems is appropriately affected by historical usage. As such, the interface through which usage information is presented to operators must be accessible to a wide demographic of operator (i.e. novice to expert), and not require intimate knowledge of systems to interpret it.

In addition, the rate at which usage information is reported to operators should also be carefully considered – too frequent and operators risk being overloaded with data, and too infrequent and operators will not necessarily be able to respond to changes in usage adequately.

4.2.3. Data Interpretation

It is suggested that possessing access to system usage profiles provides potential value to manufacturers and/or operators in three primary areas; maintenance implementation, revenue model innovation and design of systems. As stated in section 1.3, the primary purpose of usage profiling is to aid the definition of maintenance intervals, within an overall preventative approach. Objective information describing the usage of a system, continuously accessible throughout an asset's service, can be exploited over subjective personnel opinion or manufacturer definitions to enable less cautious (and thus more cost-effective) decision making.

Additional value may be found through the implementation of a shift from a static pricing model to a usage-based pricing model, supported by system usage information. Such a model would enable a manufacturer to differentiate within a crowded market whilst incentivising operators to improve operating practice and in return accept a financial cost consummate with specific usage.

Finally, manufacturers may be able to realise value through a shift towards more data-driven design processes in which usage information is leveraged to support the definition of elements of system specifications such as safety factors and materials selection. For example, currently conveyor motor specifications are typically derived from historical reference material and based upon assumed operational loads, limiting their validity. Therefore, through having access to usage information an opportunity presents for more effective designs to be produced, based upon observations of actual in-service loads.

5. CONCLUSIONS AND FURTHER WORK

A method for profiling the usage of a conveyor belt system was proposed, based upon the response of motor power consumption and speed parameters. A series of test scenarios were designed, based around the operation of an instrumented industrial conveyor belt system, to determine the feasibility of inferring system usage from the response of motor power consumption and speed parameters alone. Through inspection of acquired data it was demonstrated that the monitored parameters show sensitivity to changes in system usage, and thus can feasibly be used to infer usage. A series of measures were then defined to transform raw, time-domain parameters into proxies for usage, as a means of automating the manual process of data interpretation. The implications of implementing the proposed usage profiling concept within an industrial environment were then discussed, with data acquisition, presentation and interpretation tasks considered.

Whilst the feasibility of the proposed usage profiling concept has been demonstrated, further work will be required to realise an industry-ready solution. Thus far characterisation data from only a single system has been utilised in the development of the concept, and despite the subject system being reflective of a commonly employed format of conveyor belt system within the bulk handling industries, further testing will be required in order to determine how applicable existing understanding is to similar systems. Additionally, during the completion of Conveyor Characterisation Tests each operational variable was changed only in isolation, therefore, the effect of simultaneous variable changes should be investigated to consider all possible scenarios. Finally, to validate the veracity of the proposed concept industrial implementation will be required, enabling operator feedback to be gathered and used to direct future development.

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