Journal of Physics: Conference Series

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To cite this article: T P Waters *et al* 2024 *J. Phys.: Conf. Ser.* **2647** 172008

Design, build and test of packaging for vibration control of medical goods delivered by drone

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Abstract. The delivery of medical products by drone is potentially game-changing and promises increased speed, particularly when trying to service hard to reach rural areas, and reduced carbon emissions. However, this raises a number of questions, including the effects of flight on the stability of medical products and how this can be mitigated through the design of appropriate packaging. The aim of this study was to design and experimentally evaluate a medical goods package capable of mitigating the vibration experienced during transportation by drone. Two proposed designs have been developed that feature coil spring and wire rope isolators. Transmission of vibration by these prototype packages, together with an industry-standard product, was measured both in the laboratory and in transportation trials. The prototype packages reduced transmitted vibration by a factor of six during drone flight tests but performed slightly worse when transported by car since road inputs occur at characteristically lower frequencies. The prototypes are significantly heavier than the standard product when empty although this is partially offset by a reduction in the number of required cool packs facilitated by the use of high performance vacuum insulation panels.

1. Introduction

1.1. Drone delivery of medical products

Uncrewed Aerial Vehicles (UAVs), referred to here as ‘drones’, are being seen increasingly as a potential new mode of transport for delivering medical products to remote and hard to access areas, with Zipline being one of the foremost examples, successfully delivering blood for transfusion to clinics and hospitals across Rwanda [1]. The COVID-19 pandemic has seen the use of drones in the delivery of COVID-19 samples, blood tests and quarantine materials [2, 3] with reported benefits including increased delivery speed, reduced carbon footprint, and a reduction in physical contact between hospital staff and medical goods. Another area of interest for possible drone logistics intervention is in pharmacy aseptic services where sterile medicines such as chemotherapies are prepared for individual patients based on a national dose banding table [4]. These medicines cost the National Health Service (NHS) in England approximately £3.8 billion annually, 3% of its total annual budget [5] and can have very short shelf-lives, often measured in hours, requiring reliable logistics services in order to minimise wastage [6, 7, 8].

The opportunity to respond more dynamically in response to patients' needs using drone logistics systems has led to a projection that there will be a 25% increase in market growth for the emergency medical services domain from 2019 to 2025 [2].

1.2. Air transport regulation related to the carriage of medical products

In the UK, the Medicines and Healthcare Products Regulatory Authority (MHRA) guidance on airfreight [9] outlines that the International Air Transport Association's (IATA) Perishable Cargo Regulations (PCR) [10] and Temperature Control Regulations (TCR) [11] is the industry framework for transport of medical cargos by air. Chapter 9 of the EU GDP of Medicinal Products for Human Use [12] states that it is the distributors' responsibility 'to protect medicinal products against breakage, adulteration and theft, and to ensure temperature conditions are maintained within acceptable limits' [12]. Crucially for this project, medical packaging should 'have no adverse effect on the quality of the products, and offer adequate protection from external influences' [12]. Although vibration is not explicitly stated, should vibration be found to adversely affect medicinal products, then a package which excessively amplifies vibrations would be failing to comply with this guidance. In addition to gaining the necessary permissions to use drones in a medical logistics context, (e.g. an Operational Safety Case (OSC)), the drone operator must also provide assurance that the drone platform itself will not induce any conditions which may damage the cargo. Aseptic medicines can be susceptible to vibration [13] and healthcare regulatory authorities will want assurances that adequate research has been undertaken to quantify the vibration profile of the platform and the implications of transmission to the cargo.

1.3. Vibration experienced by medical products in-transit

Evidence suggests that some medicinal products such as proteins in biopharmaceuticals and blood can be susceptible to aggregation when exposed to vibration [14], [15]. However, little research appears to have addressed the consequences of transport related vibration exposure on the quality of medical products. In particular, vibration emanating from drone platforms poses an unknown hazard to product quality given that it generally occurs at higher amplitudes and frequencies than traditional road transportation modes such as cars and bicycles [16]. The ability of medical packaging to reduce the transmission of vibration to the product becomes a vital mitigation measure.

Practical trials using a twin four-stroke engined fixed-wing drone (running between 1100 and 3400 RPM) and a battery powered hexicopter (running between 2000–2500 RPM) suggested that observed vibration levels were higher in the latter compared to the former. At these motor speeds, both drones experienced vibration at much higher frequencies than is typical of road vehicles, which is largely below 20 Hz. The drones were used to fly Actrapid (insulin solution for injection) to quantify whether there were any adverse effects on product quality resulting from exposure to vibration during flight. In a subsequent lab analysis, all Actrapid samples passed a British Pharmacopoeia (BP) turbidity test and the medicine quality was unaffected [16]. The research concluded that:

(i) Establishing the frequency-dependent sensitivity of medicines to vibration is likely to be a prerequisite to any future transportation by drone.

(ii) The standard medical packaging used in the trials was found to be ineffective at isolating the Actrapid from drone-induced vibration, with significant amplification being observed in the case of the fixed-wing drone [16].

1.4. Existing medical packaging

Commercially available packaging for transporting patient diagnostic samples, aseptic medicines and blood stocks is designed with the specific goals of maintaining controlled temperatures and containing the goods securely during transit. To satisfy UN (United Nations) and manufacturer regulations relating to transporting thermally regulated medicine, the internal temperature within the packaging must remain between 2-8 °C and it must effectively mitigate heat transfer from the environment.

Thermal packaging solutions come in disposable and re-useable forms, examples of which are shown in Figure 1. Both options typically consist of an insulating material to reduce inward heat transfer, as well as the use of phase-change material (PCM) that draws energy (heat) from the surroundings to change from solid to liquid, acting as a coolant, hereafter referred to as ‘cool packs’. The disposable, cardboard-based packaging (Figure 1(a)) is often used in the transportation of aseptic medicines which are typically bespoke-made for the patient. These packages are relatively low-cost, utilising basic insulating materials such as expanded polystyrene (EPS) to insulate the inner chamber and single-use, water-filled plastic pouches for coolant which are pre-frozen. The cardboard outer box is not waterproof and must be kept dry to maintain its structural integrity. As far as practicable, all elements of the disposable packaging are re-cycled by the receiving hospital trust after receipt.

The Versapak (Figure 1(b)) is an example of a reusable package and is ubiquitous across NHS England for the movement of patient diagnostics, blood stocks and a variety of other medical products between surgeries and pathology labs where routine milk-round logistics services are warranted. In these operations, there is a constant demand, requiring a flow of empty Versapaks back through the system from the consignee to the consignor. The insulation for these packages comprises a PU foam (30 mm thick) with a reflective foil layer to mitigate radiative effects and the package incorporates a zip to open and reseal the goods compartment, integrated handles for transportation and a water-resistant nylon fabric on all faces. The medium Versapak used in the experiments reported in this paper has external dimensions of 460mm x 260mm x 310mm and an inner chamber of 400mm x 225mm x 195mm. In the case of both types of packaging, a significant number of cool packs are required in order to maintain temperature, often far exceeding the weight of the medicinal products being transported.

(a) Disposable (b) Re-usable (Versapak)

Figure 1. Examples of commonly used medical packages.

To the authors’ knowledge, no medical packages have been designed to mitigate against transmission of vibration. This paper reports on a project to engineer and trial a prototype package to mitigate the effects of vibration resulting from both drone and road-based transport modes whilst maintaining thermal control to current legal requirements.

2. Laboratory Benchmarking

A medium Versapak was chosen as a reference package for benchmarking purposes. Its vibration isolation performance was tested on a large (Derritron VP85) single axis electrodynamic shaker. Measurements focussed on a frequency range of 0-200 Hz and were restricted to the vertical (Z) direction which was predominant in earlier drone flight trials [16]. One uniaxial accelerometer was fixed to the base plate of the shaker to measure the input acceleration and a second secured to the inside of the package. The response signals to a broadband excitation were acquired using a Data Physics Quattro frequency analyser from which the vibration transmissibility from the shaker table to the package was evaluated.

Figure 2 depicts the transmissibility of the reference package, in three different test configurations:

- "No contents", acceleration transducer placed directly on the base of the reference package with no other contents.
- "Rigid mass", transducer secured to a 1 kg dumbbell weight, placed in the reference package.
- "Saline bags", three saline bags placed in the bottom of the reference pack, with two 1 kg dumbbell weights on top, in place of cool packs. A plywood board was used to distribute the load over the three saline bags. The accelerometer was secured to the saline bag in the centre.

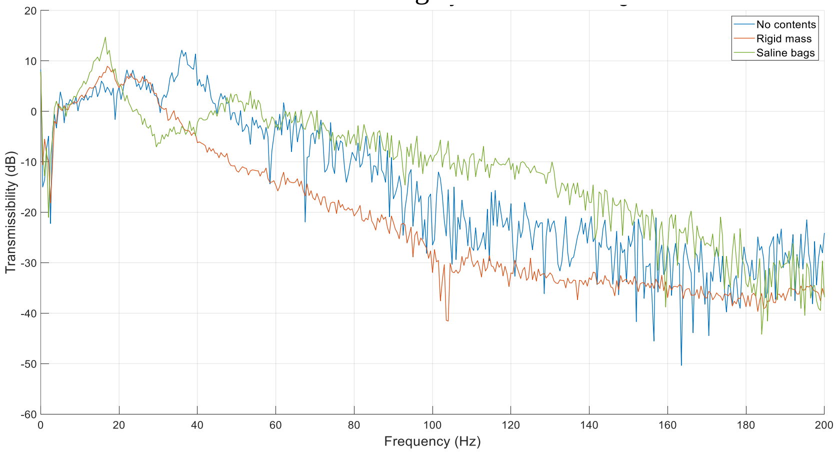


Figure 2. Acceleration transmissibility of reference package. Measurements below 3 Hz are unreliable due to instrumentation limitations.

All curves follow the classic shape expected of a vibration isolation system. At low frequencies (<10 Hz) the vibration inside the reference package is comparable to that of the shaker table on which it is mounted. Isolation begins at 30-60 Hz, depending on the configuration, and reaches -20 to -40 dB at high frequencies. In the 15-40 Hz region, resonances are apparent which amplify the input vibration by as much as 14 dB in the case of the saline bags. This maybe a result of the mass of the dumbbell weights oscillating on the stiffness of the saline bags.

3. Prototype Design

3.1. Concept

The brief was to design, build and test a prototype medical package of comparable mass and thermal performance to the reference package but improved vibration isolation performance. Consideration was also given to containment of medical products in the event of an impact but assessment of the package's crashworthiness was beyond the scope of the project.

Various 'box-within-a-box' configurations were considered to accommodate thermal insulation and vibration isolation systems independently. It was chosen to isolate an insulated box rather than insulate an isolated box to minimise the volume that needed to be cooled. The inner box comprised a thermal insulation chamber that fitted snugly into a containment chamber, Figure 3. The thermal chamber was an assembly of vacuum insulation panels (VIP), supplied by KevothermalTM. The VIP surfaces were lined with anti-microbial material. The containment chamber was manufactured from carbon composite for strength and lightness. This inner box was resiliently mounted on springs within an outer box made from polypropylene panels, the base of which was rib stiffened to improve rigidity and hence vibration isolation performance. To achieve the same footprint as the reference package, the assembly was designed to fit within the existing Versapak's water-resistant outer skin, one specimen of which had already been sacrificed for material testing purposes. This also ensured that the prototype could be accommodated by any drone platform that had been designed specifically for the reference package. The total unladen mass of the prototype package was 7.9 kg, significantly heavier than the reference package at 2.53 kg. However, the adoption of VIPs facilitated weight savings of the fully laden package by reducing the number of cool packs required, as discussed later.

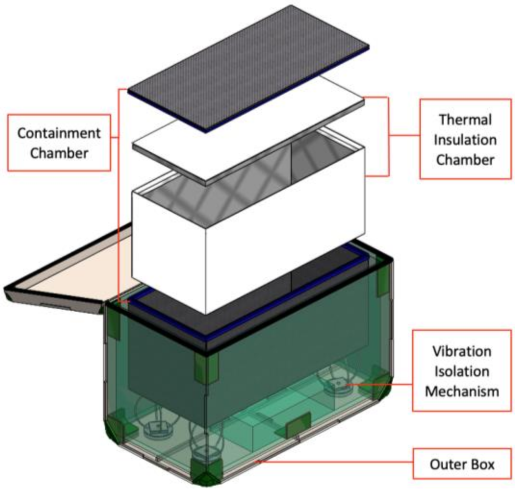


Figure 3. Design concept for prototype medical package

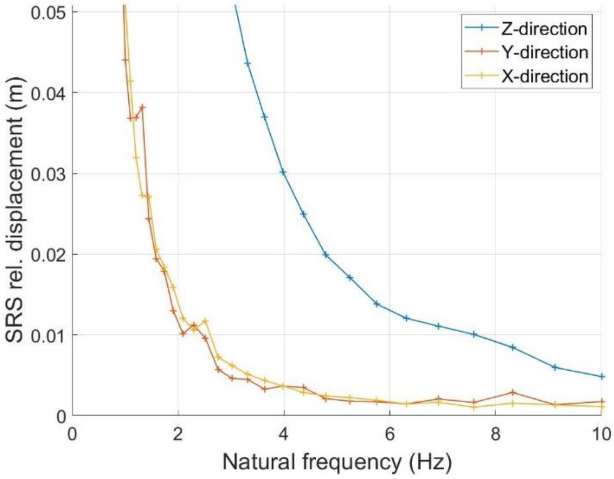


Figure 4: Shock response spectra of relative displacement for typical excitations on a fixed wing drone

3.2. *Rattle Space Considerations*

Shock Response Spectra (SRS) of relative displacement were computed to predict the required rattle space between the containment chamber and the outer box and also, the maximum stroke of the isolator springs. The input waveform for the analysis was taken from flight test data acquired on a fixed wing drone [16] and the peak response of a single degree-of-freedom system was calculated numerically for a range of natural frequencies using the ODE45 solver in Matlab. The results of this analysis are shown in Figure 4.

The figure shows that the required rattle space is an order of magnitude larger in the vertical direction compared to the lateral directions. The dimensional constraints of the proposed design allowed for a rattle space of about 20 mm which imposed a lower limit on the natural frequency in the vertical direction of 5 Hz. Rattle space in the lateral directions is easily achieved, although the analysis assumes that vibration in the X and Y directions only arises due to excitation in the corresponding direction, i.e. cross-coupling is not taken into account. Vibration levels for road-based transport are higher at such frequencies which may necessitate a larger rattle space for some road vehicle types.

3.3. *Vibration Isolator Selection*

Wire rope isolators (WRI) were chosen to facilitate vibration isolation between the outer box and the containment box, as shown in Figure 5(a). Unlike coil springs, these provide lateral constraint through their shear stiffness and also increased damping due to friction between the spiral strands. The containment box together with its typical payload were estimated to be 2.8 kg. Enidine CR4-400 mounts were chosen to give a predicted tangent stiffness of about 1 $\mathrm{Nmm^{-1}}$ under a nominal static load of 6.9 N per mount resulting in a fundamental natural frequency of 6 Hz in the vertical direction.

Owing to long lead times on the delivery of the WRI isolators, an alternative design was conceived that featured coil springs, as shown in Figure 5(b). The nominal stiffness of each spring was 0.61 N/mm giving a predicted natural frequency in the vertical direction of 4.7 Hz. In addition to the four vertically orientated coil springs, a further eight springs were mounted in the horizontal plane to provide lateral constraint. The springs were mounted in 3D-printed seats as shown.

(a) WRI springs (b) Coil springs

Figure 5: Prototype packaging designs with vibration isolation

4. Laboratory Testing of Prototypes

4.1. Shaker Table

The coil spring and WRI prototype packages were tested on the electrodynamic shaker using the same instrumentation and procedure as for the benchmark testing. A ‘lightly loaded’ configuration was chosen. The transmissibility was measured in the vertical direction between the base plate and within the insulation chamber, at a position representative of the placement of medical goods. The acceleration transmissibility for both the WRI and coil spring prototype packages are compared with the reference package in Figure 6.

The coil spring prototype package had a resonance at 7 Hz, slightly higher than its intended value. There was also a slight resonance at 10 Hz, due to a suspected rocking mode, and transmission of -20 to -40 dB was achieved above about 12 Hz. The WRI prototype package had a fundamental resonance at 16 Hz. This was significantly higher than intended and compromised isolation performance significantly below 60 Hz. Experimental characterisation of the WRI springs was not possible due to time constraints but their nonlinear behaviour is one potential source of discrepancy. The resonance peak was lower in amplitude than that for the coil spring prototype package owing to higher inherent damping in the WRIs. The reference package exhibited more highly damped resonances, but its isolation performance was found to be inferior over much of the frequency range, particularly between 60-100 Hz which is typical of multi-copter drone self-excitation.

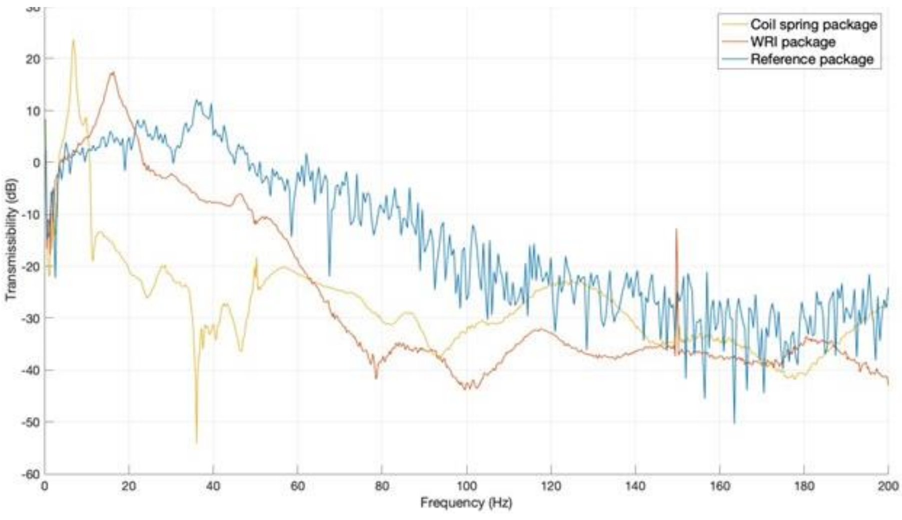


Figure 6: Comparison between measured acceleration transmissibility functions from prototype coil spring and WRI prototype with reference package

5. Transportation Testing

A series of transport tests were conducted (i) to compare typical vibration spectra from cars and drones and (ii) to assess the vibration isolation performance of the two prototype packages in real vibration environments. Packages were transported together where possible but independent runs were often required, either due to payload limitations or because the coil spring and WRI prototype packages shared the same interchangeable thermal chamber.

For each test, the reference package was loaded with three 250 mL saline bags, in addition to 2 kg of dumbbell weights to represent ice packs. A load-distributing plywood board was used to ensure the weights did not move around during transit, thereby fixing the centre of mass. Two triaxial Axivity data logging sensors were used to acquire acceleration signals. One was placed on the vehicle and another in the base of the reference package. Power spectral densities (PSD) were calculated for each of the three orthogonal directions and summed to obtain resultant acceleration levels. However, the lateral directions were found to contribute little to the resultant levels in all cases. Octave spectra were synthesised from the narrowband PSDs.

5.1. Road Transport

Road transport tests were conducted on a set route, representative of a typical journey a medical courier would take between Southampton Red Funnel ferry terminal (the key transit point, and a hub for medical delivery traffic, linking the Isle of Wight to Southampton) and Southampton General Hospital, where pathology samples are analysed. The route followed public roads starting from the entrance to the passenger ferry terminal to the main entrance of the hospital, a journey of some 6.5 km taking 22 minutes by car in free flow conditions. The car used was a diesel-powered Volkswagen Golf.

Figure 7 shows the PSDs of the measured accelerations inside each of the packages when transported by car. Also shown is the input vibration as measured at a reference position beneath the packages. Figure 8 shows the level difference between the vibration levels inside the packages and the input vibration. There is a prominent peak in the input vibration level at 2 Hz due to the suspension of the vehicle, then falls by an order of magnitude by 20 Hz. The 7 Hz mounting resonance of the coil spring prototype package is clearly apparent causing about 14 dB amplification. Vibration isolation is substantial from 10 – 30 Hz but appears more modest at higher frequencies, due in part to the noise floor of the instrumentation. The WRI prototype package amplifies vibration at about 10 Hz, lower than its resonance measured in laboratory tests. Its isolation performance is comparable to the reference package until 30 Hz, above which a benefit of up to about 10 dB is seen.

Figure 9 (a) shows octave band and overall vibration levels. The latter are 7% and 18% higher for the two prototype packages owing to amplification in the 4 and 8 Hz centre frequency bands.

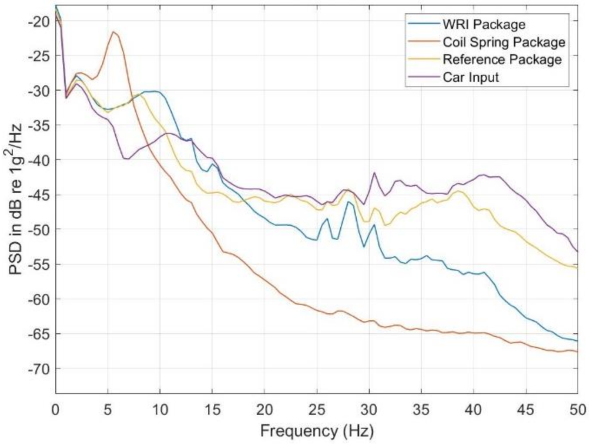


Figure 7. Resultant acceleration PSDs for packages transported by car.

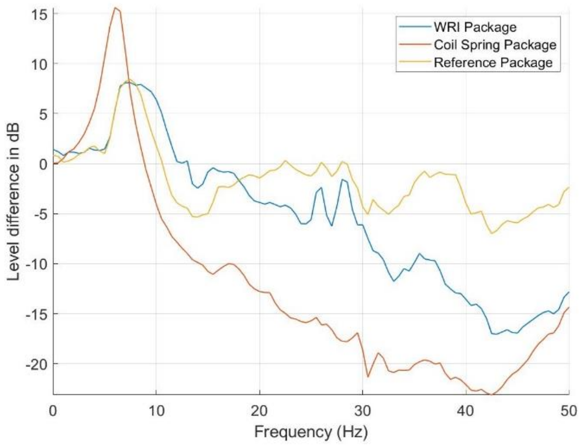
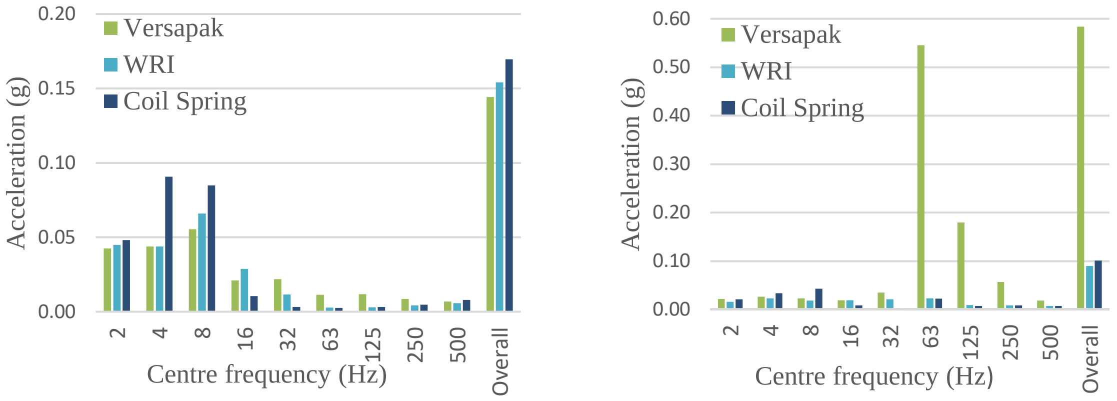


Figure 8. Level difference between vibration levels within packages and input vibration in car.



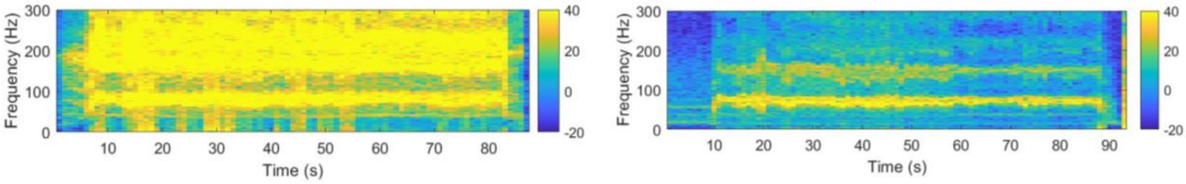
(a) Car **(b)** Drone

Figure 9 Octave band spectra and overall acceleration levels

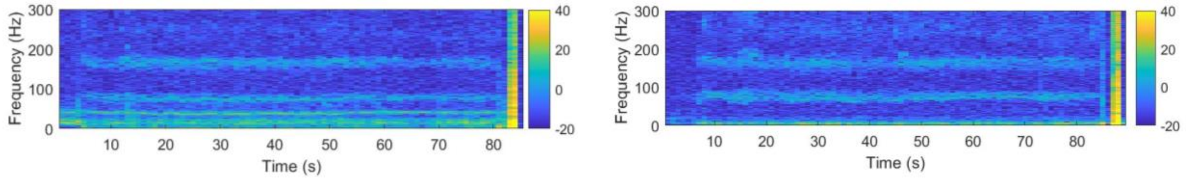
5.2. Drone Transport

Flight testing of the packages was undertaken using a custom-built Titan hexacopter drone which was provided and piloted by Motion Robotics, UK. The Titan is specifically intended to perform remote drop-deliveries of underslung packages. The flight plan comprised take-off, forward flight (200 m), a slight banked turn (20°), another period of forward flight (200 m), a 15 seconds hover, landing and a release of the package (0.2 m drop). Each flight lasted approximately 90 seconds.

Figure 10 shows spectrograms of the measured accelerations in each of the three orthogonal directions. Vibration of the airframe (Figure 10 (a)) is highest, particularly in the vertical (z) direction. The reference package (Figure 10 (b)) provides substantial isolation but appreciable vibration is still seen at the 'blade passing' frequency of about 50 Hz and its first harmonic. The WRI (Figure 10 (c)) and coil spring (Figure 10 (d)) prototype packages are both effective at isolating these predominant excitation frequencies, which is consistent with the laboratory based transmissibility measurements in Figure 6. The broadband transient at the end of the flight corresponds to the impact of the package with the ground on release.



(a) Airframe (b) Reference package



(c) WRI prototype package (d) Coil spring prototype package

Figure 10. Hexacopter drone spectrograms of vertical acceleration. Scale is in dB (ref arb.)

Figure 11 shows the resultant PSDs based on acceleration signals measured during forward flight and hover stages. Figure 12 shows the level difference between vibration levels inside the packages and the input vibration from the drone. Above 50 Hz, the two prototype packages perform similarly to each other and provide over 20 dB of benefit compared to the reference package. Between 10 Hz and 40 Hz the WRI package performs comparably to the reference package whereas the coil spring package provides about 10 dB of additional attenuation. Below 10 Hz the coil spring package shows a particularly prominent resonance, as seen in the car transport data. Figure 9(b) shows the octave and overall vibration levels. Both prototype packages transmit about one-sixth of the overall vibration when compared to the reference package, due largely to the superior isolation in the predominant 63 Hz centre frequency band.

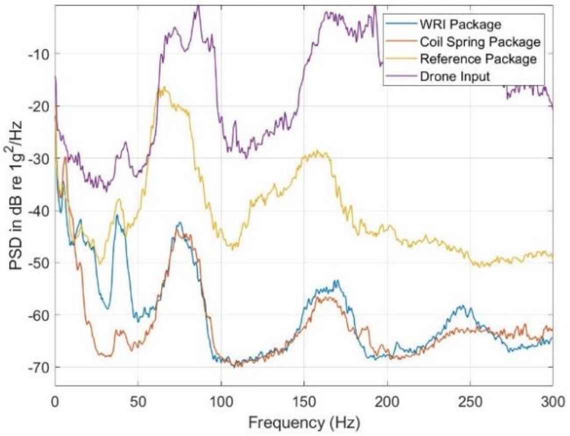


Figure 11. Resultant acceleration PSDs for packages transported by drone

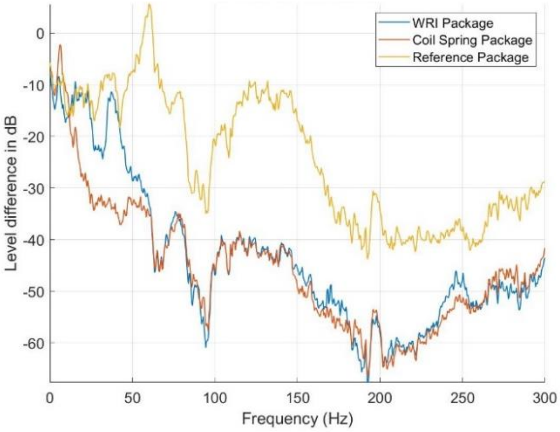


Figure 12. Level difference between resultant vibration levels within packages and input vibration in drones

6. Conclusions

Medical packaging is commercially available that provides sufficient thermal insulation and secure containment of contents but none has been designed to mitigate transmission of vibration. Motivated by the potential for medical deliveries by drone, this paper reports on the design, build and test of a prototype package that additionally provides vibration isolation. Two variants of the prototype were built, using coil springs and wire rope isolators. Laboratory testing was conducted on a shaker table to quantify the vibration transmission in the predominant, vertical direction. The coil spring variant provided isolation above about 12 Hz, broadly in line with design calculations, whereas the wire rope isolator variant was stiffer than intended which deferred isolation to about 25 Hz. Both prototype packages provided superior isolation performance to a commercially available package in these isolation frequency regions. Below these frequencies the isolators amplify vibration, more so than the benchmark reference package which has potential implications for onward transportation by road. Field trials were also undertaken, both for road and drone transport. The prototype packages successfully isolated drone vibration at the predominant excitation frequencies resulting in a six-fold reduction in vibration transmission compared to the reference package. However, modest disbenefits were seen in the case of road transport in which excitation predominantly occurs below 20 Hz.

7. Future Developments

This preliminary feasibility study has served to highlight the challenge of drone vibration in the context of transportation of medical goods, and has demonstrated a proposed solution to a proof-of-concept stage. Future work is required to address many outstanding issues, including the following:

- The prototype variant based on wire rope isolators is the preferred arrangement as they implicitly provide constraint in all directions and their inherent damping is higher. Similar, softer isolators will be purchased to lower the frequency at which isolation is obtained.
- Simple, 1.2 m drop tests (not reported here) caused damage to some 3D printed components. Alternative materials will be selected.
- Drop tests need to be conducted in line with test procedures published by the Vehicle Certification Agency in the UK [17].
- Further light-weighting of the prototype package is required.

8. Acknowledgements

Funding for this work was provided by the UK EPSRC as part of the E-Drone project [grant number EP/V002619/1] (www.e-drone.org), and by the UK Department for Transport as part of Solent Transports ‘Future Transport Zones’ project (www.solent-transport.com/solent-future-transport-zone/). The authors are grateful to Motion Robotics (https://www.motion-robotics.co.uk/) for providing and piloting the drone used for flight testing.

References

[1] Lin C A, Shah K, Mauntel L C C and Shah S A. 2018 Drone delivery of medications: Review of the landscape and legal considerations. *Am J Health Syst Pharm*.**75**(3):153-8.
[2] Ilancheran M. 2020 Covid-19, medical drones, & the last mile of the pharma supply chain.
[3] Walawalkar A. 2020 Nhs using drones to deliver coronavirus kit between hospitals.
[4] Chatelut E, White-Koning M L, Mathijssen R H, Puisset F, Baker S D and Sparreboom A. 2012 Dose banding as an alternative to body surface area-based dosing of chemotherapeutic agents. *Br J Cancer*.**107**(7):1100-6.
[5] Lord Carter of Coles. 2020 Transforming nhs pharmacy aseptic services in england. Department of Health and Social Care.
[6] Shaughnessy A F. 2012 Monoclonal antibodies: Magic bullets with a hefty price tag. *BMJ : British Medical Journal*.**345**:e8346.
[7] Gilbar P J, Chambers C R and Gilbar E C. 2017 Opportunities to significantly reduce expenditure associated with cancer drugs. *Future Oncol*.**13**(15):1311-22.
[8] Cortes J, Perez-García J M, Llombart-Cussac A, Curigliano G, El Saghir N S, Cardoso F, Barrios C H, Wagle S, Roman J, Harbeck N, et al. 2020 Enhancing global access to cancer medicines. *CA Cancer J Clin*.**70**(2):105-24.
[9] Medicines & Healthcare products Regulatory Agency. 2019 Guidance on air freight: Medicines & Healthcare products Regulatory Agency; [Available from: https://www.gov.uk/government/publications/guidance-on-distribution-and-importation-of-medicines-and-active-substance-from-approved-countries/guidance-on-air-freight-as-part-of-the-contingency-planning-for-the-uks-departure-from-the-eu.
[10] IATA. 2023 Perishable cargo regulations (pcr): IATA; [Available from: https://www.iata.org/en/publications/store/perishable-cargo-regulations/.
[11] IATA. 2023 Temperature control regulations (tcr): IATA; [Available from: https://www.iata.org/en/publications/store/temperature-control-regulations/.
[12] Official Journal of the European Union. 2013 Guidelines of 5 november 2013 on good distribution practice of medicinal products for human use (text with eea relevance) 2013/c 343/01.
[13] Fleischman M L, Chung, J., Paul, E. P. and Lewus, R. A. 2017 Shipping-induced aggregation in therapeutic antibodies: Utilization of a scale-down model to assess degradation in monoclonal antibodies. *Journal of Pharmaceutical Sciences*.**106**(4):994-1000.
[14] Hii M S Y, Courtney, P. and Royall, P. G. 2019 An evaluation of the delivery of medicines using drones. *Drones*.**3**(3).
[15] Torisu T, Maruno T, Yoneda S, Hamaji Y, Honda S, Ohkubo T and Uchiyama S. 2017 Friability testing as a new stress-stability assay for biopharmaceuticals. *J Pharm Sci*.**106**(10):2966-78.
[16] Oakey A, Waters, T., Zhu, W. Q., Royall, P. G., Cherrett, T., Courtney, P., Majoe, D. and Jelev, N. 2021 Quantifying the effects of vibration on medicines in transit caused by fixed-wing and multi-copter drones. *Drones*.**5**(1).
[17] Vehicle Certification Agency. 2022 Dangerous goods transporting by drone: Vca – caa test procedure for crash protected containers.