Assessing Pilot Response to Low-Frequency Disturbances: A Literature Review

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Abstract

Many international modelling and simulation capabilities for the assessment of flying difficulty for shipboard launch and recovery operations only consider airwake-related disturbances in the 0.2-2 Hz range as contributing to pilot workload. Recent work assessing the impacts of ship motion on helicopter operations shows that these disturbances occur in a frequency range below 0.2 Hz and therefore might also have the potential to impact pilot workload due, in part, to high energy content. This paper briefly examines the presence of ship motion effects in a ship's airwake, and performs a literature review on the significance of these effects to pilot workload. Although current literature is inconclusive, this paper serves to align future work.

1. Introduction

In modern naval aviation, helicopters provide exceptional tactical utility. They can perform takeoff and landings at sea via the flight deck located at the back of large ships, as shown in Figure 1.

Unfortunately, the airwake above the flight deck of these ships can be extremely turbulent and complex. Unsteady aerodynamic loading caused by turbulence in a ship's airwake and ship motion due to ocean waves yields varying levels of difficulty for maritime helicopter pilots performing landings at sea. Factors such as sea state, relative wind conditions, and flight deck motion can all have an effect on the workload of these pilots. Quantifying pilot workload is critical for determining Ship-Helicopter Operational Limits (SHOL), or in other words, the operational envelope for maritime pilots performing landings at sea [2].


Figure 1: Helicopter approaching HMCS Montreal [1]

Several of the factors attributing to pilot workload can be observed through airwake disturbances to the pilot. These disturbances that the pilot must manage in flight can take many forms, but the most studied are those resulting from unsteady aerodynamic loading of the helicopter fuselage and rotor in the ship's airwake. Unsteady aerodynamic loading occurs in the presence of high-energy turbulent eddies and flapping shear layers [3]. Workload can be related to the magnitude of these psuedo-random disturbances to the pilot, specifically through the use of a Power Spectral Density (PSD) plot across the frequency range at which disturbances occur. Historically, the frequency range of disturbances said to have the greatest impact on pilot workload was from 0.2 to 2 Hz [3] [4]. This will be referred to as the "traditional frequency range".

Since the majority of disturbances seemed to occur in this region, it became common practice to exclude any higher or lower motion frequencies from analysis. However, it has become clear that most of the largest disturbances, seen as peaks on a PSD plot, occur at the lower end of the spectrum. In a subset of this low range, from 0.07 to 0.14 Hz, the most dominant disturbances are related to ship motion [5].

Knowing that these disturbances can be anywhere from 2-10 times greater than those in the 0.2 to 2 Hz traditional range, and that they would normally be overlooked when determining pilot workload, this report serves to revisit the traditional range in order to more accurately link unsteady aerodynamic loading caused by ship motion to pilot workload to the development of simulated SHOL envelopes.

First, the presence of large disturbances outside of the traditional range caused by ship motion will be presented. This will be followed by a review of current literature regarding pilot response to low-frequency disturbances, to determine if documented evidence exists which shows that low-frequency disturbances actually impact pilot workload. Finally, next steps will be discussed.

2. Large ship-motion disturbances outside of the traditional frequency range

Disturbances to helicopter pilots operating in a ship's turbulent airwake can be observed by using anemometers to measure wind conditions at several points above the flight deck, either through trials at sea, or through use of a wind tunnel to replicate relative wind conditions. Alternatively, the airwake can also be modelled using Computational Fluid Dynamics (CFD). Building a time series model for the airwake over the flight deck facilitates observation of the effects of certain parameters over the airwake, such as different wind directions or sea conditions. The anemometer time series data can then be transformed using the *pwelch* function in Matlab, which uses Welch's power spectral density estimate. Power Spectral Density (PSD), refers to the strength of energy variance for a given frequency, and is obtained by taking a Fast Fourier Transform. This shifts the observation from the time domain to frequency domain. For this analysis, the PSD for certain frequencies such the turbulent energy variance in the airwake, is of interest.

The PSD of the wind speed vector magnitude for a handful of test cases used in a previous study [6] will be briefly examined to show typical frequency content in ship-motion conditions. The data were collected at sea in realistic operating conditions above the flight deck of a HALIFAX-class frigate. The test cases are composed of different flow speeds and wind directions. The wind direction denotes the origin of the wind with respect to the longitudinal axis of the ship running from bow to stern. Following naval customs, wind from starboard side will be referred to as Green, and wind from port side as Red. The angle follows likewise, measured with respect to the longitudinal axis at the bow. The flow speed is given in knots. A summary of the four example cases is shown below in Table 1.

Name	Wind Origin	Angle (deg)	Flow Speed (kts)
G30-Regular-1	Starboard	30	35.8
G30-Regular-2	Starboard	30	18.1
R30-Regular-1	Port	30	24.8
R30-Regular-2	Port	30	37.3

Table 1: Summary of test cases

In Table 1, the names given to each case are composed of four parts: the flow origin direction (red/green), angle (degrees), wave type, and trial number. For this brief analysis, only regular wave profiles are considered. In this context, regular can be interpreted as periodic uni-directional waves in Sea State 4 or below. Weather conditions were not identical between cases, however it can be assumed that the wave profiles are similar. Time histories of ship pitch motion angles for Green and Red cases can be seen in Figures 2 and 3 respectively. These show the motion of the flight deck over time for the given cases, and will be compared to the airwake above the flight deck. It can be interpreted from Figures 2 & 3 that the frequency of sinusoidal regular ship motion is about 0.02 Hz. When accounting for the frequency shift from the dynamic response of the ship [7], it is reasonable to expect that the ship motion effects present in the airwake will be around 0.08-0.1 Hz, as observed in other studies.

For each of these cases, the magnitude of the flow speed vector 9.5 m above the centre of the flight deck (the nominal high hover position of the helicopter rotor disk) was also measured, then normalized to the undistorted relative wind speed (a value for the

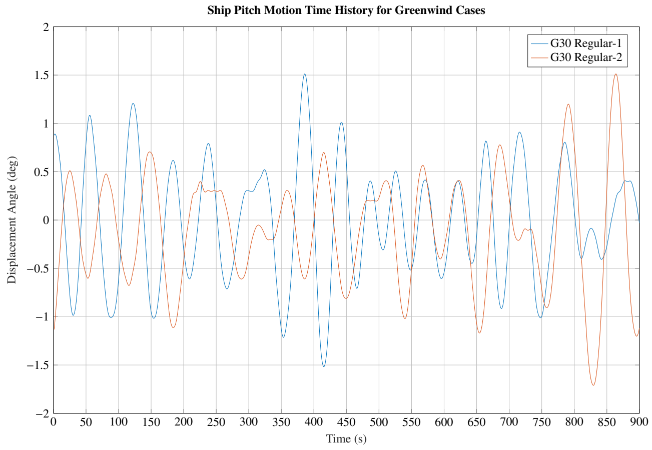


Figure 2: Ship motion pitch angle time history for Green cases

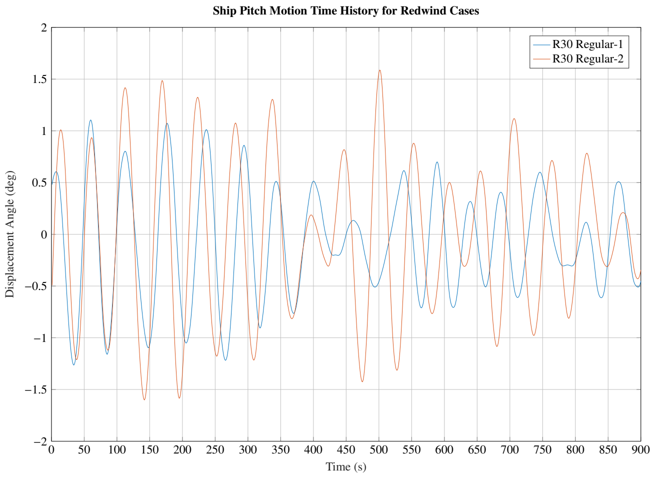


Figure 3: Ship motion pitch angle time history for Red cases

measured wind used to estimate the idealized undistorted wind over the ocean at ship anemometer height [8]). This yielded characteristic non-dimensional flow vectors ranging from 0 to 1. Spectral density plots shown in Figures 4-7 were then used to present the turbulent airwake energy variance over a frequency range from 0 to 2 Hz with a frequency resolution of 0.005 Hz. All of these figures show a large peak just below 0.2 Hz, aligning with other studies noting a high concentration of spectral power in the low end of the spectrum, specifically from 0.1-0.2 Hz [2] [9]. Note that the y-axis of these plots is shown on a log scale.

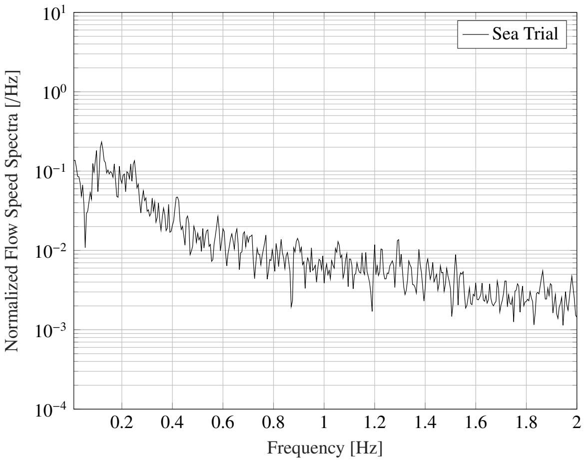


Figure 4: PSD for G30-Regular-1

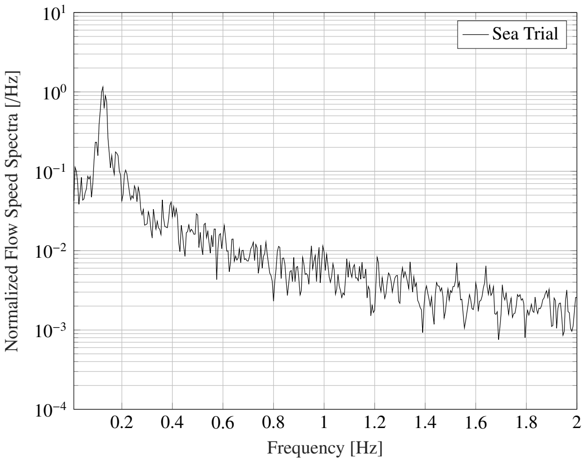


Figure 5: PSD for G30-Regular-2

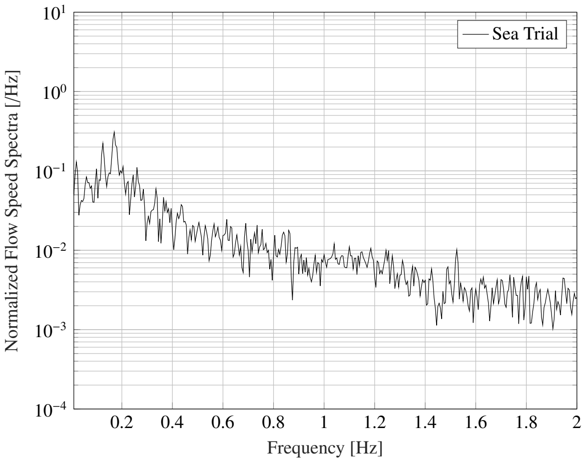


Figure 6: PSD for R30-Regular-1

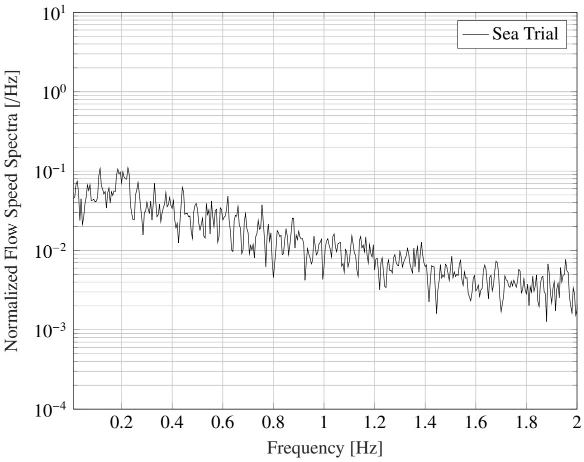
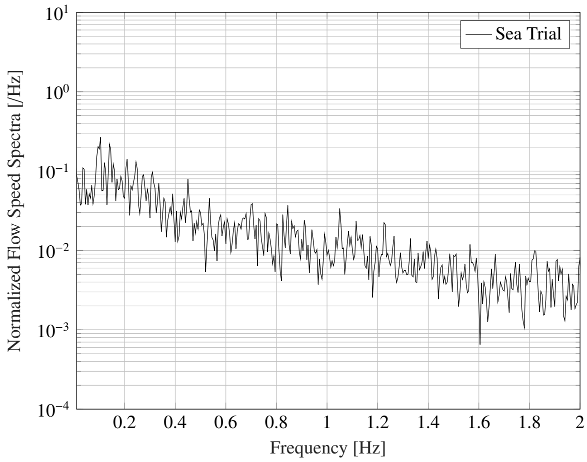


Figure 7: PSD for R30-Regular-2

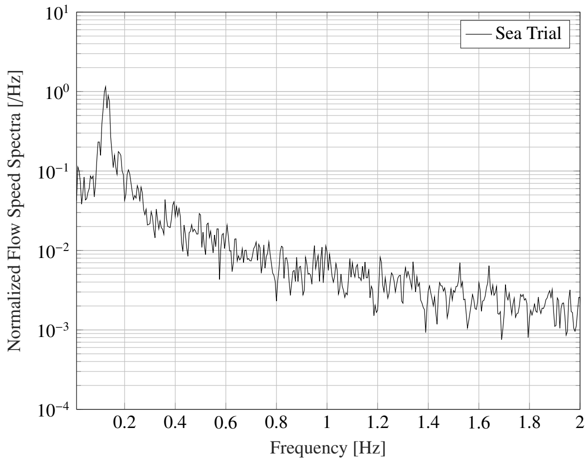
These spectral density plots can then be compared to cases for which no ship motion is present. For basic illustration, the power spectral density for two cases with G30 winds will be compared. Figure 8 shows the comparison for a G30 case with negligible ship motion alongside one with regular periodic ship motion. Although the peak seen on the PSD without ship motion outside the traditional range still exists, it is significantly lower than the peak observed in a case containing ship motion.

Although it has been observed that peaks can occur below 0.2 Hz, when no ship motion is present, peaks due to ship motion can be considerably higher in magnitude.

To further illustrate how much larger the peaks below 0.2 Hz can be, a comparison between those below 0.2 Hz and those inside the traditional 0.2 to 2 Hz range was performed. For each of the four cases, the peak spectral density value from 0 to 0.2 Hz was divided by the peak spectral density value inside the traditional range. Figure 9 shows the results of this comparison for each case. It can be easily observed that for most of the cases considered in this report, the peak value below 0.2 Hz is larger than the peak value from 0.2 to 2 Hz based on ratios larger than 1. The low-frequency peaks can even be up to one order of magnitude greater such as in G30 Regular 2, which suggests that these high-power, low frequency disturbances have the potential to impact pilot workload, even if workload for those frequencies is legitimately lower than in the traditional frequency range. To summarize, the existence of large peaks on a PSD plot associated with ship motion and below 0.2 Hz also correspond with known ship motion frequencies. As the collective understanding of the ship-helicopter dynamic interface improves, it is worth revisiting the traditional range of disturbance frequencies assumed to impact pilot workload when performing shipboard landings.



(a) PSD for G30 winds without ship motion



(b) PSD for G30 winds with ship motion

Figure 8: Comparison of PSD for G30 case with and without ship motion

3. Pilot response to low-frequency disturbances in literature

Having shown the existence of these disturbances in standard sea trial data, it is now important to consider whether or not these high-energy, low-frequency disturbances have any significant effect on pilot workload when performing at-sea landings.

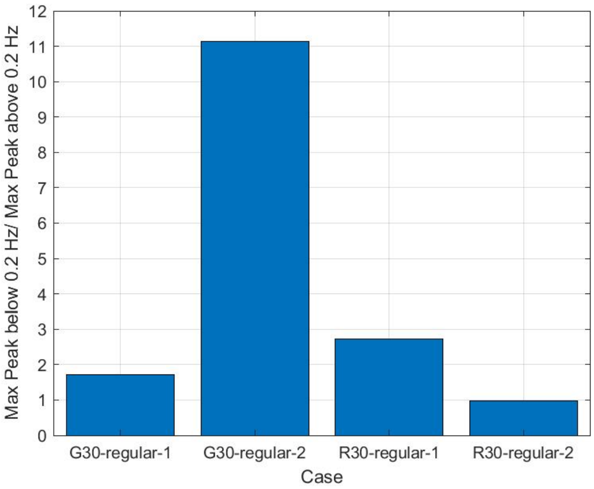


Figure 9: Ratios of peaks below 0.2 Hz to those inside the 0.2-2 Hz range

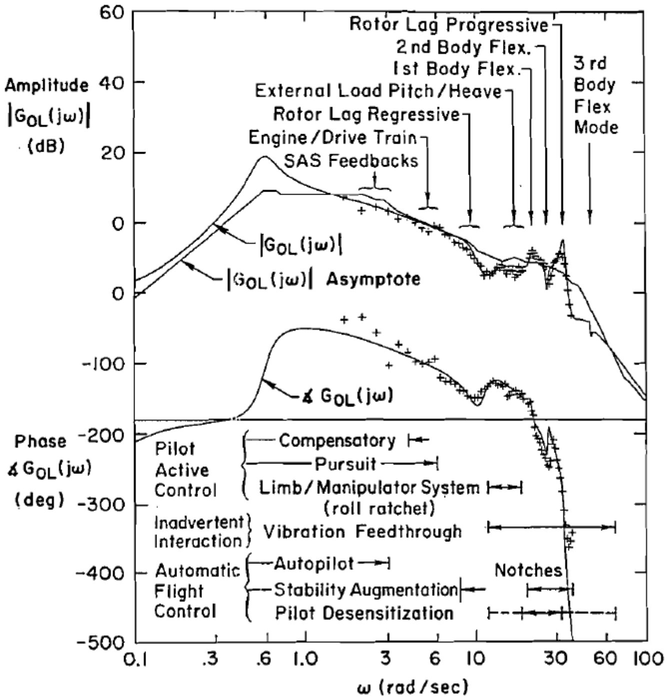


Figure 10: Roll rate to cyclic transfer function of a large modern helicopter, reproduced from [10]

First, it's useful to inspect the primary source used by most ship-helicopter operations publications when discussing the closed loop pilot response range. McRuer's 1994 publication in the International Journal of Control, *"Interdisciplinary interactions and dynamic systems integration"*, is often referenced when claiming that the frequency range of disturbances which most affect a pilot's workload is from 0.2 to 2 Hz (1.26-12.57 rad/s). This paper highlights interactions between several dynamic systems in a helicopter. Figure 10, taken from this paper [10], shows a Bode plot describing the transfer function for a large helicopter. This figure seems to be the most plausible source for the origin of the low-limit in the traditional range. However there are no clearly defined statements regarding the traditional frequency range. Notably, there are observable peaks near 0.5 rad/s (about 0.08 Hz) on the amplitude portion, which is interestingly inside the range for disturbances caused by ship motion (0.07 to 0.14 Hz).

In McRuer's paper, the 2 Hz high-limit is more clearly defined. At frequencies greater than 10 rad/s (about 1.6 Hz), biodynamic coupling can occur. Biodynamic coupling refers to the combination of the pilot's neuromuscular system and the stick. During biodynamic coupling, the pilot may not even notice any vibrations at all [10], thus significantly reducing the workload.

When considering the 0.2 Hz limit, the answer may in fact lie as a consequence of pilot anecdotal evidence. In *"Interdisciplinary interactions and dynamic systems integration"*, McRuer references his 1974 publication, *"Mathematical models of human pilot behavior"* [11]. This paper touches upon compensatory versus pursuit control systems, and mentions the difficulty for pilots to track quasi-predictable sinusoidal motion. It has been stated that pilots are in fact adept at tracking and replicating quasi-predictable sinusoidal motion above a frequency of 0.5 Hz. However, below this threshold, the frequency is too low for active pattern detection, and at very low frequencies (below 0.1 Hz), the pilot can only work to reduce the error instead of actually predicting or tracking motion [11]. This doesn't directly speak to the pilot's response to which type of disturbances can contribute to increased workload, but it may not be unreasonable to suggest that disturbances caused by ship motion at low frequencies have the potential to make at-sea landings more difficult to helicopter pilots as they may have trouble with motion tracking at this frequency. Perhaps historically, the acts of tracking ship motion and operating in an unsteady airwake were considered in isolation, as opposed to the combined nature observed in modern testing. Regardless, references by McRuer do not confirm or explain the reason for the 0.2 Hz lower limit.

Although these references are often used for narrowing analysis to the traditional frequency range, different studies have also noted that the highest power concentration, or dominant input frequency, is around 0.1 Hz [9; 12; 13]. These studies present the PSD for several types of input conditions, however their analysis usually does not extend to include the workload or output from the pilots themselves.

Another study, performed by Rowe in 2001 describes disturbances above 10 rad/s as low-magnitude vibrations which have little effect on the pilot [14], aligning with McRuer's earlier statements [10] and helping to cement the idea of a 2 Hz high-limit for the significant disturbance frequency range. Rowe further explains that disturbances in the 1-10 rad/s range will rotate and push the aircraft, forcing the pilot to assume closed-loop manual control. Finally, it is stated that at frequencies below 1 rad/s (about 0.16 Hz), large disturbances can force the pilot to reach for severe control input, which greatly contributes to pilot workload. This supports the inclusion of low-frequency disturbances in determining pilot workload.

Furthermore, pilot anecdotal evidence suggests that one of the greatest contributors to workload is pedal use [2]. Large peaks in pedal control input at frequencies around 0.1 Hz observed by Forrest (2012) in *Ship-helicopter operating limits prediction using piloted flight simulation and time-accurate airwakes* could be linked to increased pilot workload. The largest peaks in PSD for pedal control were linked to the most difficult landings. However, it was suggested that these large peaks in pedal input control were applied gradually, and thus did not significantly increase pilot workload.

Other literature exists which seems to support the exclusion of low-frequency disturbances, suggesting that these large disturbances are usually slow to manifest and therefore do not contribute much to pilot workload [3]. Contrarily, this same study suggests that most pilot activity is at the lowest end of the 0.1-1 Hz spectrum, which actually stretches below the traditional range to include more low-frequency disturbances. An important note is that this study doesn't include ship motion (only wind conditions), which makes it difficult to explain the relationship between disturbances caused primarily by ship motion and pilot workload. Perhaps aerodynamic disturbances below 0.2 Hz are slow to manifest, but those caused by ship motion may be more difficult to deal with.

Therefore, it would seem that modern literature is conflicted by the inclusion or exclusion of low-frequency disturbances caused by ship motion. The purpose of the study usually dictates the frequency range chosen. If accurate modelling and simulations are desired, then many publications will reduce the range in order to more efficiently create simulations and representations of ship airwake data. The typical goal of ship airwake studies is to examine the input to the pilot in terms of the airwake conditions, often only examining what a supposed pilot control block would be receiving as an input signal. However, in order to better model pilot response and workload in shipboard operations, it may be more effective to examine the pilot output alongside the input values. This could allow for better calculation and correction of the error between the current and ideal pilot control model.

4. Conclusions

In conclusion, understanding the fidelity of the traditional 0.2-2 Hz frequency spectrum as a closed-loop pilot response range is a complex matter. This traditional range has no distinct origin, and is so widely accepted in modern literature and publications, that uncovering its fidelity is near impossible. The high limit of 2 Hz seems fairly ubiquitous, however it is at the low end of the spectrum that things begin to break down. It is generally well understood that the greatest peaks in PSD occur at lower frequencies, usually around 0.1-0.2 Hz, however it is the understanding of how disturbances below 0.2 Hz affect pilot workload that seems to be mostly unexplored. This report served to answer two questions:

- *Are there significant disturbance peaks just below the 0.2 Hz cutoff value?*
- *Do they add significant difficulty to pilots, or noticeably increase pilot workload?*

Section 2 used real airwake data taken from sea trials in realistic conditions to present the existence of these large disturbance peaks just below the 0.2 Hz cutoff frequency. It was seen that these peaks can likely be attributed to ship motion. Low-frequency ship motion disturbances were observed to be over 10 times larger than those in the traditional range for some cases. The large peaks can be observed throughout other studies as well, denoting a high concentration of turbulent energy at around 0.1 Hz.

Section 3 then attempted to link these large disturbances caused by ship motion to their effect on pilot workload. The origin of the traditional 0.2 to 2 Hz range was found to be unclear in terms of the 0.2 Hz lower limit, and so a review of modern literature was necessary. Here it seems there are both arguments for the inclusion of disturbances lower than 0.2 Hz, as they are very large and have the potential to force the pilot to use severe control input, thus greatly increasing workload, as well as those which claim that high-magnitude, low-frequency disturbances are slow to manifest themselves and thus do not pose much challenge for an experienced pilot.

What is clear is that the specific contribution of ship motion towards pilot workload when performing at-sea landings in the turbulent airwake of a ship is not yet well understood. Further studies are needed to specifically assess the response of helicopter pilots to these strong but low-frequency disturbances. The control inputs and subjective opinions of pilots should be compared to the airwake data, with hopes of more closely linking specific types of disturbances to their effect on pilot workload. Additional pilot anecdotal evidence is required to supplement airwake data, in order to understand if disturbances and control input actually impact flying difficulty. Perhaps it might also be worth revisiting the idea of using pilot workload as the metric for flying difficulty. At the time of writing, current literature suggests that there is no clear reason for the inclusion or exclusion of these disturbances from the traditional range, even though the impact of these large disturbances is not well-understood. As the collective understanding of the ship-helicopter dynamic interface improves, it is worth revisiting the fundamental and key assumptions on which the model is built.

5. References

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