Hand Vibration Analysis due to Impact Equipment

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Abstract. Several human health problems can arise due to the load transmission from impact equipment manipulated directly with the operator's hands. These issues can also extend to the upper limbs. Equipment such as stone breakers exhibit significant vibration levels during operation, and understanding how the intensity and duration of this vibration affect the loads transmitted to the operator is necessary to assess potential mitigation during work. Therefore, this study aims to perform an operator's hand numerical model, using the finite element method, while operating the stone breaker, with input data on the vibration caused by the stone breaker. The objective is to determine the level of stress imposed and the resulting transmissibility to the worker's hands. In addition, examining the changes in these values resulting from the position modifications where the worker holds the equipment. Three different positions for the operator to hold the brittle were used: 0°, 45°, and 90°. The natural frequency of the hand was also varied according to the literature, with models at 30 Hz and others at 50 Hz. It was found that the grip position at 45° and the natural frequency of 30 Hz were the cases most likely to affect the operator's health.

Keywords: hand-arm, vibration, stone breaker, FEM.

1 Introduction

Manually performed tasks by humans, using impact tools such as grinders, jackhammers, drills, and demolition hammers, remain necessary today. These types of equipment can cause injuries when used for prolonged periods, as they exhibit significant vibration levels, leading to conditions like hand-arm vibration syndrome (HAVS) and other musculoskeletal injuries [1]. Hands are vital tools for humans, enabling a variety of tasks, not only in work but also in leisure activities. They are considered the most important segments of the upper limbs, and according to social security data, they are the parts most frequently injured in work-related incidents, leading to temporary or even permanent absences, and causing psychological and economic damage to employees and employers [2]. Thus, it is important to understand how vibration levels affect worker health and propose measures to mitigate vibration during work [3].

Vibration exposure is divided into two main types: whole-body vibration (WBV) and hand-arm vibration (HAV) [4]. The World Health Organization (WHO) has listed various problems that body vibration can cause, such as carcinogens, ergonomic risks for back pain, and noise. WHO reports that 16% of hearing loss, 37% of back pain, and 13% of chronic obstructive pulmonary diseases are related to the work environment [5]. Furthermore, HAV can cause white finger syndrome (Raynaud's syndrome), compromising the hand's sensorineural part, and carpal tunnel syndrome [4].

In this context, this study aims to investigate the effect of vibration transmitted by a stone hammer, during use, to workers' hands. Thus, hand-arm vibration (HAV) caused and transmitted by the equipment will be studied using a numerical model employing the finite element method (FEM). Due to its complex anatomy, the model will focus on the bones of the hand, primarily the carpal bones, metacarpal bones, and phalanges, which are divided into proximal, medial, and distal [6]. The model will help understand stress levels and resulting transmissibility in the hands, as well as whether the position in which the worker holds the equipment influences these results. Analyzing these factors can contribute to developing ergonomic and safety guidelines that minimize health risks to operators.

The importance of this study lies in the potential to provide a better understanding of vibration transmission mechanisms and their consequences for occupational health. It is expected that the results obtained can guide the implementation of safer work practices and the improvement of impact tools and equipment design, thereby reducing the adverse effects associated with prolonged vibration exposure.

2 Literature Review

Vibration can be defined as a movement around a fixed point with constant or variable acceleration. There are two main types of vibration exposure in the human body: whole-body vibration (WBV) and hand-transmitted vibration (HTV) [4]. Prolonged exposure to vibration can cause a range of health issues, including hand-arm vibration syndrome (HAVS) and other musculoskeletal injuries. According to [7], HAVS is a medical condition that can result in damage to blood vessels, nerves, muscles, and joints in the hands and arms, caused by prolonged exposure to vibrating tools. Another study by [8] discusses the effects of vibration exposure and associated musculoskeletal injuries, highlighting that impact tools such as grinders and drills are common sources of vibration that can lead to these problems.

Tools like pneumatic rock breakers are the main cause of acute injuries among miners due to their weight and are associated with very high levels of noise and vibration [9]. Mitigating risks associated with vibration exposure is crucial in ergonomic research. Strategies to reduce vibration effects include modifying equipment design to minimize vibration transmission, using damping materials, and implementing safe work practices. Proper training for workers in handling techniques and the use of personal protective equipment are also important measures. Griffin [3] highlights that integrating these strategies can significantly reduce the incidence of HAVS and other related disorders.

Knowledge transfer regarding vibration mitigation across different industries can benefit a wide range of sectors, promoting the implementation of effective ergonomic practices and improving occupational safety [10]. The human body has a wide variety of components, such as muscles, bones, nerves, and cartilage, among others. Each body segment, as well as each tissue, has a specific vibration frequency, most of which is below 100 Hz. Consequently, exposure to this frequency range is highly detrimental [5]. Among these, it is important to mention that hands have frequencies of 30-50 Hz [5]. Figure 1 presents a schematic overview of the literature on natural frequency ranges of the human body [5].

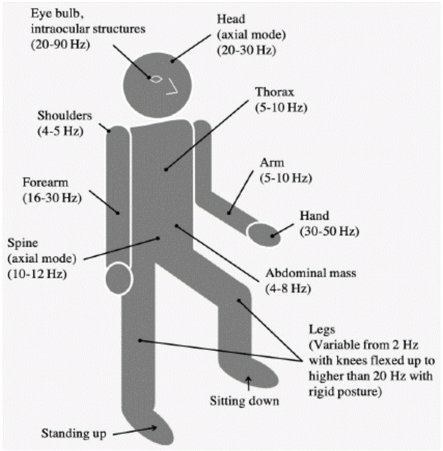


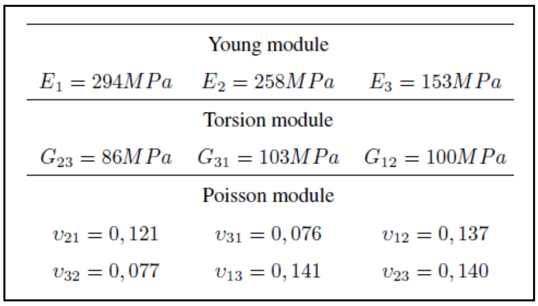
Figure 1. General representation of main frequencies in the human body [5].

Vibration analysis using FEM simulates the biomechanical response of hands when operating vibrating tools, allowing precise assessment of occupational risks. This method enables modeling anatomical structures, and the model's detail level depends on available data and expected response. Wang et al. [11] identify four types of numerical models:

- The most commonly used models are lumped parameter models, which include lumped masses and discrete stiffness and damping elements, used to represent dynamic responses of hand and arm at specific locations but are challenging in predicting contact pressure at hand-handle interface or stress in tissues.
- Multibody models are widely used to predict hand-arm vibrations based on anatomical structures, but they cannot predict contact pressures.
- Finite element models. FE models can represent the dynamics of hands and arms, as well as stress in soft tissues and bones.
- Hybrid models, combining features of three aforementioned models. They can analyze the coupling effect between active muscle force and vibration characteristics of the model.

Material data is necessary for FEM analysis. Bones have a porous structure and need to be modeled as linear, heterogeneous, and anisotropic solid material. Silva et al. [12] measured their Young's, Poisson's, and torsion moduli, with results presented in Table 1.

Table 1. Bones mechanical properties [12].



	Young module	
$E_1 = 294MPa$	$E_2 = 258MPa$	$E_3 = 153MPa$
	Torsion module	
$G_{23} = 86MPa$	$G_{31} = 103MPa$	$G_{12} = 100MPa$
	Poisson module	
$\upsilon_{21} = 0,121$	$\upsilon_{31} = 0,076$	$\upsilon_{12} = 0,137$
$\upsilon_{32} = 0,077$	$\upsilon_{13} = 0,141$	$\upsilon_{23} = 0,140$

3 Methods

For stress and transmissibility analysis using the finite element method, the hand model included distal, medial, proximal phalanges, and metacarpals. The model, provided by Oliveira et al. [13], consists of tetrahedral elements (CTETRA) generated in the commercial software Hypermesh®. Figure 2 shows the hand model.

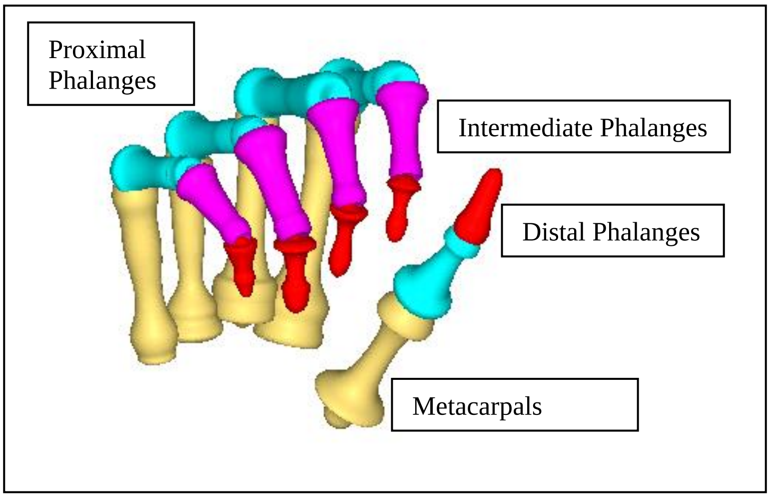


Figure 2. Hand FEM model

Initial modal analysis on the other hand was performed to obtain natural frequency as reported in literature, between 30 and 50 Hz. One model was calibrated at 30 Hz and the other at 50 Hz. Six models were generated to reach frequency values at the extremes of intervals for three possible different gripping positions of a machine operator. Figure 3 shows the configurations of these models.

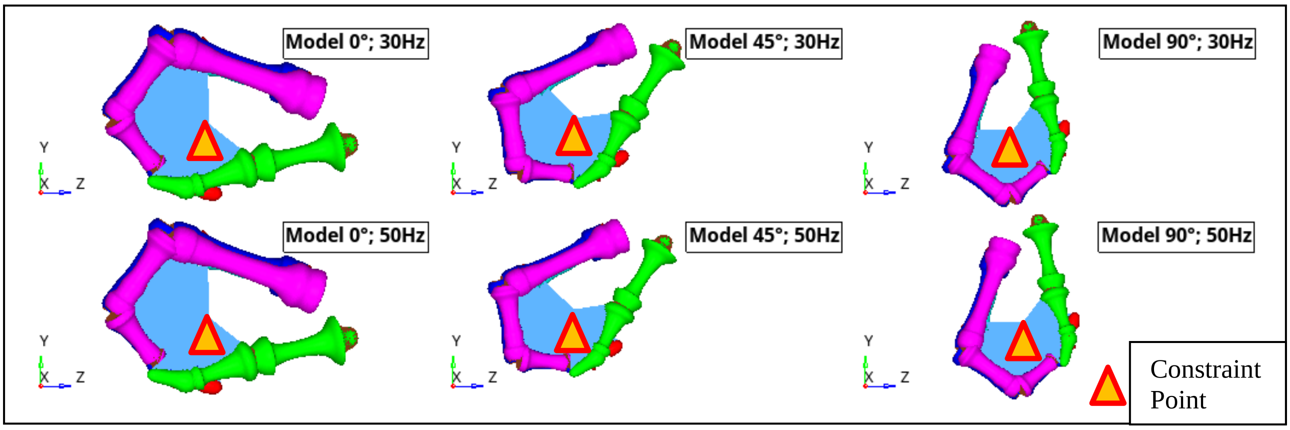


Figure 3. Models configurations used to achieve natural frequency

After configuring the hand model to its desired natural frequency, the same models were set up for a frequency domain analysis. The frequency range analyzed was between 25 Hz and 55 Hz, covering the interval indicated in the literature. Accelerations were applied at the point previously used as fixation. Figure 4 shows one of the described models, indicating the point where accelerations were applied.

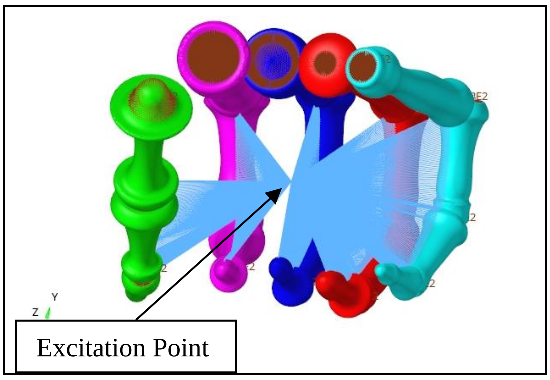
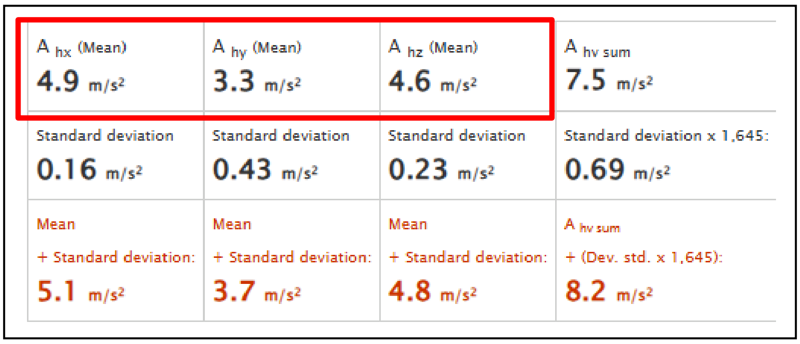


Figure 4. A complete model for stress and transmissibility analysis

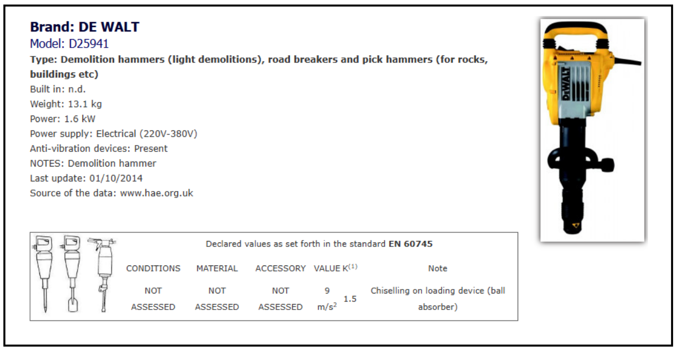
Acceleration values at the excitation entry point, representing the demolition hammer, as indicated in Figure 4, were taken from the Portale Agenti Fisici database [14] and are shown in Figure 5. Values on the X, Y, and Z axes from the first row, highlighted in the table, were used.



A_{hx} (Mean) 4.9 m/s²	A_{hy} (Mean) 3.3 m/s²	A_{hz} (Mean) 4.6 m/s²	$A_{hv\ sum}$ 7.5 m/s²
Standard deviation 0.16 m/s²	Standard deviation 0.43 m/s²	Standard deviation 0.23 m/s²	Standard deviation x 1,645: 0.69 m/s²
Mean + Standard deviation: 5.1 m/s²	Mean + Standard deviation: 3.7 m/s²	Mean + Standard deviation: 4.8 m/s²	$A_{hv\ sum}$ + (Dev. std. x 1,645): 8.2 m/s²

Figure 5. Axis X, Y, and Z, accelerations value [14]

The chosen demolition hammer was the DeWalt model D25941, powered electrically. Figure 6 illustrates the model.



Brand: DE WALT

Model: D25941

Type: Demolition hammers (light demolitions), road breakers and pick hammers (for rocks, buildings etc)

Built in: n.d.

Weight: 13.1 kg

Power: 1.6 kW

Power supply: Electrical (220V-380V)

Anti-vibration devices: Present

NOTES: Demolition hammer

Last update: 01/10/2014

Source of the data: www.hae.org.uk

Declared values as set forth in the standard **EN 60745**

CONDITIONS	MATERIAL	ACCESSORY	VALUE	K$^{(1)}$	Note
NOT ASSESSED	NOT ASSESSED	NOT ASSESSED	9 m/s^2	1.5	Chiselling on loading device (ball absorber)

Figure 6. Demolition hammer, DeWalt. [14]

Acceleration transmission between the hammer and hand model was done using rigid elements (RBE2), without considering any damping. The Opstruct® software was used as the solver and Hyperview® software for post-processing the previously described analyses.

4 Discussions

After completed analyses, stress and acceleration results transmitted in each model were verified and compared. Figure 7 shows stress results in hand bones at different positions and their respective natural frequencies.

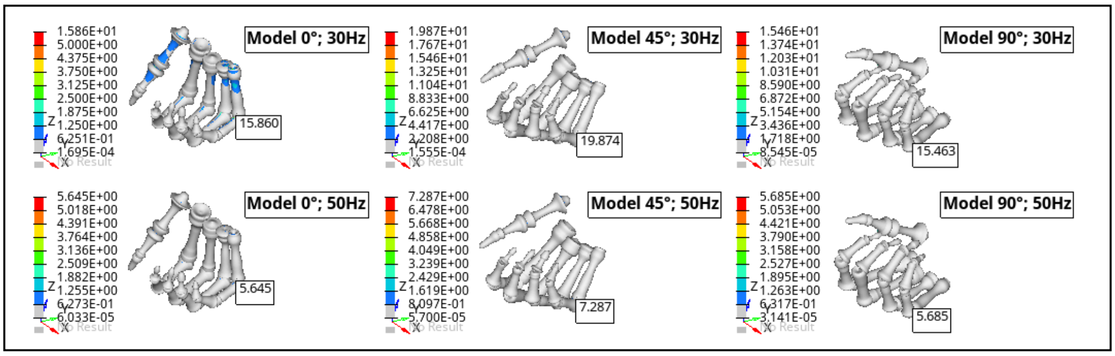


Figure 7. Six models stress values

It is observed that stress values were higher for the 45° grip position and did not show significant variation between 0° and 90° positions. It is also noted that the region of maximum stress did not change across the six model configurations. Figure 8 shows stress behavior across frequencies for each model.

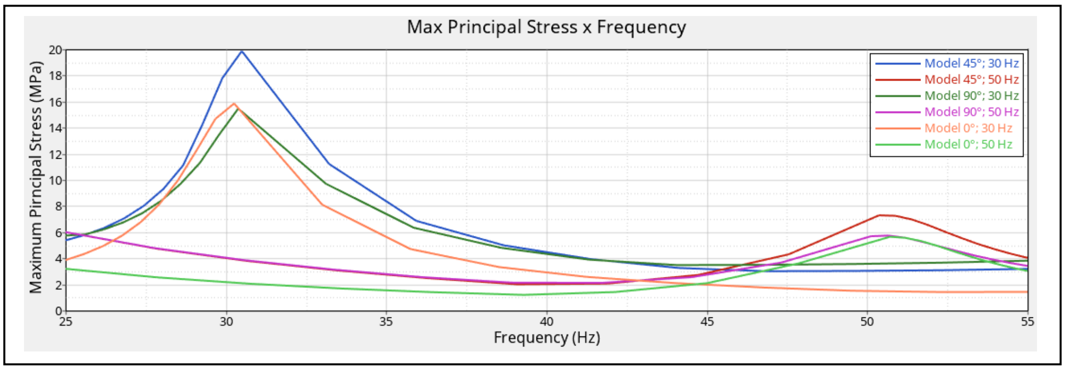


Figure 8. Stresses behavior across frequencies for each model.

A significant stress decrease is observed at higher frequencies from the 30 Hz models to the 50 Hz models. The difference in stress between the first observed stress at 25 Hz and the natural frequency of 50 Hz was not significant. Acceleration results, in magnitude, showed the same stress behavior, being higher in the 45° models and with little difference between the 0° and 90° models. Additionally, the region with maximum accelerations corresponded to the region with maximum stress. Figure 9 shows the acceleration results.

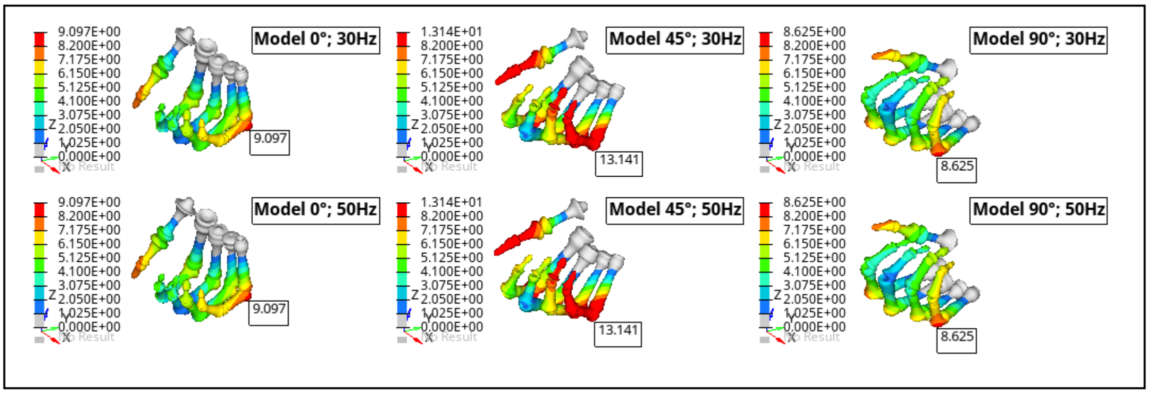


Figure 9. Six model accelerations result in m/s^2

Figure 10 shows the acceleration behavior graph across frequency. It is observed that the peaks at natural frequencies were the same among models of the same position and different natural frequencies.

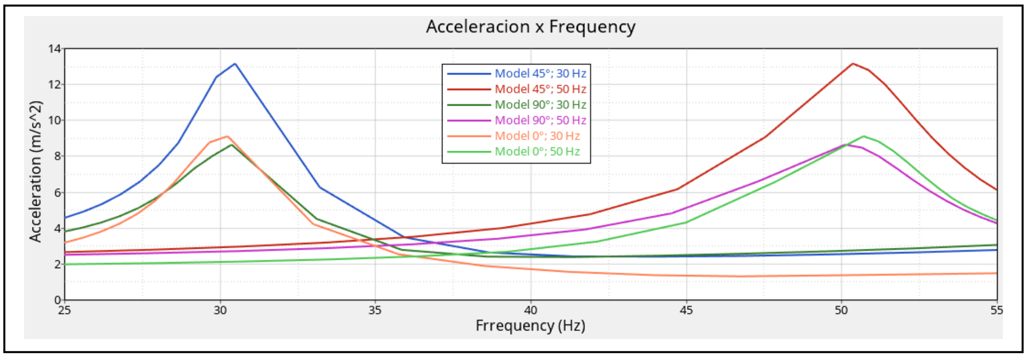


Figure 10. Acceleration behavior across frequencies for each model.

Simulation results demonstrated an operator higher probability of experiencing issues at lower frequencies, likely due to higher amplitude, as the amplitude acceleration values were the same. The highest stress value obtained was 19.9 MPa with the 45° fixation model and natural frequency of 30 Hz, compared to a lower value of 5.6 MPa for the 0° fixation model and natural frequency of 50 Hz, being the difference 255%. Among models of the same position, the stress difference in the 45° model ranged from a high of 19.9 MPa to a low of 7.3 MPa, a difference of 173%. For 0° models, it ranged from 15.86 MPa to 5.65 MPa, 181%, and for 90° models, it ranged from 15.43 MPa to 15.69 MPa, resulting in a difference of 171%. Acceleration transmissibility, as expected, does not change with the model's natural frequency. Considering the same position, there is lower transmitted acceleration for models in 0° and 90° positions compared to the 45° position model, approximately 52% lower.

5 Conclusions

The present study demonstrated that the operator's fixation position at 45° for equipment handling had a higher tendency for potential health risks to the operator. This conclusion was based on the higher amplitudes of transmitted stresses and accelerations observed at this position. It was also found that the highest stress levels occurred when the model exhibited a lower frequency, due to the larger amplitudes recorded at 30 Hz compared to 50 Hz for the same system.

The presented results can assist in decision-making regarding the optimal positions for equipment handling to mitigate health risks to operators. Furthermore, methodologies can be applied to alter the natural frequencies of operators' hands, such as personal protective equipment that increases these frequencies. Consequently, companies can implement better practices and training for equipment handling, improving workplace quality and safety.

Occupational accidents and diseases have significant impacts not only on the directly affected individuals but also on the healthcare system and the economy as a whole. Investing in studies and practices that reduce health risks for workers is essential for promoting a safe and sustainable work environment, reducing absenteeism and medical expenses, as well as enhancing workers' quality of life.

It is important to note that the methodology presented for predicting stress and acceleration levels can be applied to various types of equipment and numerical models, with varying degrees of detail. Additionally, physical tests are recommended to be correlated with the presented concepts.

Acknowledgements.

To Universidade Federal de Minas Gerais (UFMG) and their Professors. Also to CAPES as Finance Code 001.

Authorship statement.

The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors or has the permission of the owners to be included here.

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