# Structure Optimization Study of Hard Disk Drives to Reduce Flow-Induced Vibration

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**Abstract:** In this paper, the effects of two flow-induced vibration (FIV) mitigation components on hard disk drive (HDD) airflow, vortex splitters and flow diverters, were verified. The edges of the components were also modified by filleting and the resulting effect on airflow determined. A perspective review on HDDs and their operation, and the mechanism and mitigation of FIV was discussed. Three suitable turbulent models from the commercial fluid flow solver FLUENT were briefly compared. A preliminary study was then carried out on a simplified HDD model to determine the mesh fineness required in HDD turbulent flow simulation in order to obtain accurate results. Another study was done to compare between the RNG $k$-$\varepsilon$ and LES turbulent models in FLUENT. A full 3.5 inch commercial HDD model was used and results indicated that the LES model was suitable for turbulent flow modelling of a HDD. Lastly, flow simulation of three HDD models with different FIV mitigating features was carried out. Results showed that flow diverters are effective in reducing airflow turbulence in HDD for *Re* of $12.5\text{x}10^4$. The modification and filleting of component edges to make them more aerodynamic streamlining was shown to be less effective but further studies should be done to conclude on the effectiveness of filleting. An optimized HDD structure which includes both vortex splitters and flow diverters, with the filleting of component edges recommended but not mandatory was proposed.

**Keywords:** Hard disk, turbulence, flow-induced vibration, structure optimization, Reynolds number.

## I. INTRODUCTION

A Hard Disk Drive (HDD, Fig. **1**) is an essential part of our world today. The incredible ability of a HDD to store and preserve large amounts of data together with a fast rate of data recording and retrieving has made it the dominant device for data storage in computers. With the development of technology, the demand for intensive storage space and the read/write speeds of HDD has been steadily increasing over the years. Engineers have been making efforts to research on ways to increase the capacity of HDDs while not compromising their functionality and operation. The recording density of hard disk has been noted to increase 60% yearly and is projected to reach 1Tb/in$^2$ by 2012, while future hard drives are expected to rotate at speeds up to 20,000+rpm [1, 2].

However, the failure tendency of HDDs increases as rotation speed and track density increase to cope with the increasing demands. The higher rotation speed causes increased airflow turbulence within the HDD and promotes structural vibration of the interior HDD components [3]. The vibration of the HDD arm and Head Gimbal Assembly (HGA) reduces the positioning accuracy of the magnetic head and results in track misregistration (TMR) and HDD errors [1]. These cause what is commonly known as a ‘HDD crash’, where the HDD malfunctions and stops working, which often leads to data loss.

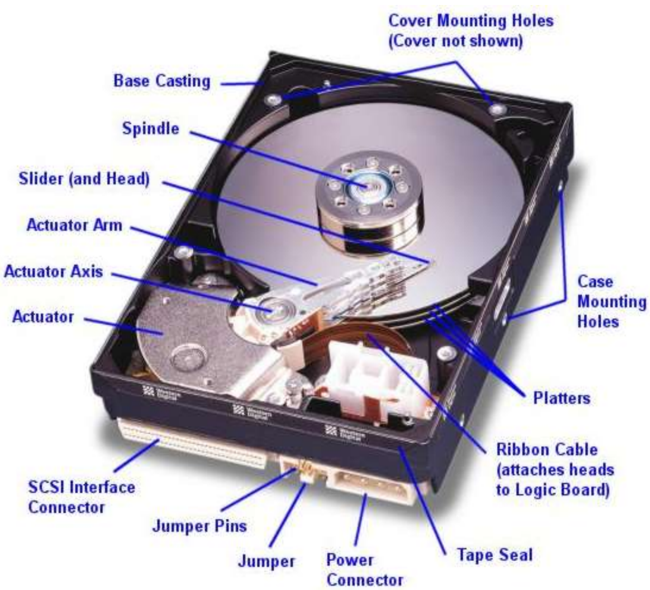


**Fig. (1).** Interior of a typical HDD.

In order to meet the increasing demands of HDD capacity and speed, engineers have to understand the mechanism of flow-induced vibrations (FIV) and the effectiveness of FIV mitigation components. The typical HDDs of today have components such as vortex splitters and flow diverters in their interiors to reduce airflow turbulence and FIV. This

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paper focuses on combining the concepts of aerodynamic design and streamlining with the incorporation of FIV mitigation components.

## II. PAST WORKS ON HDD'S

### A. Flow-Induced Vibration (FIV)

The accurate positioning of a read/write head and slider is controlled by a system that comprises a servo system with a servo loop (Fig. **2**). The servo loop feeds back positional information of the hard disk slider to a position controller, where adjustments can be made to the actual position of the slider to meet more closely to the exact requested position. The actual position of the slider differs from the request position due to several disturbances of the servo system, namely 2 classifications: repeatable run-out (RRO) and non-repeatable run-out (NRRO) [4].

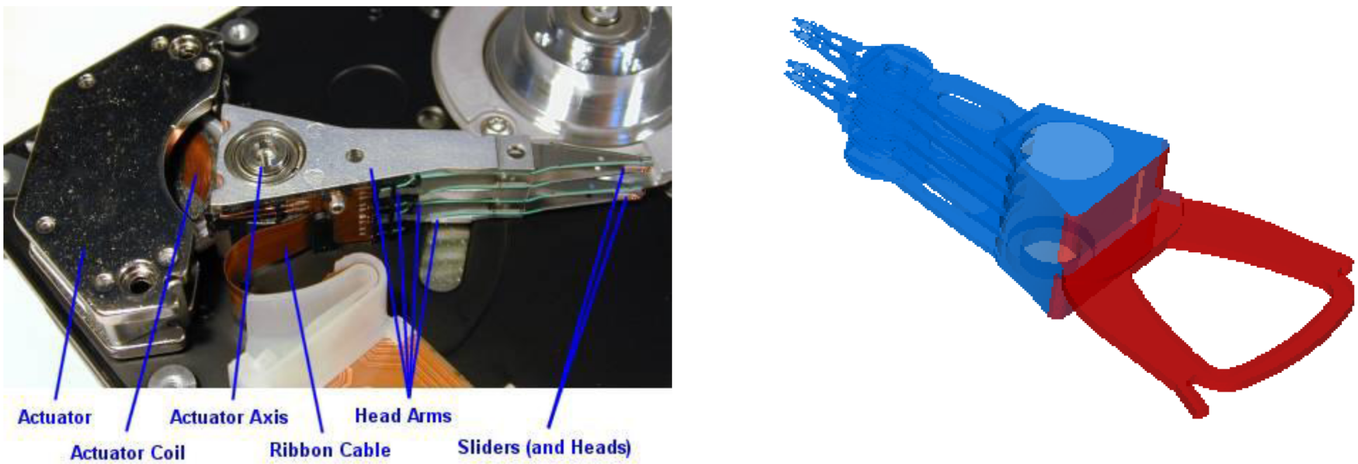


**Fig. (2).** A HDD Arm assembly (**left**) and a HDD Arm (**right**).

RRO is a vibration frequency that changes the position of the hard disk slider with respect to data tracks in a predictable manner. Examples are vibration resulting from tolerances in the motor-hub assembly and resonant frequencies in the actuator assembly. RRO is predictable and techniques such as vibration damping and designing components to vibrate at frequencies different from that of the servo system have always been taken to minimize it. However, NRRO is an unpredictable and random vibration frequency. It is mainly caused by vibration and is difficult to minimize simply by using servo system filters or damping.

Typical hard disk platters are spun at a speed of 5400rpm up to 10000rpm [5] or even more. The rapid airflow in the interior of a HDD is highly unsteady with partly laminar and partly turbulent regions, and consists of three regions: 'a solid body inner region near the hub, an outer region dominated by counter rotating vortices and a boundary layer region near the shroud' [6, 7]. The turbulent airflow generates unsteady pressure fluctuations or aerodynamic force known as 'windage', causing structural vibration of the HDD components [8].

Numerous studies on FIV focus on the design of the hard disk arm. Shimizu *et al*. [8] revealed that pressure fluctuations were generated by vortex shedding from the suspensions and the E-block (HDD arm). Another study also showed that airflow directed towards the outer circumference of the disks collides with the arm, creating a wake region. The velocity profile is distorted and causes pressure fluctuation [3]. The pressure difference created between the upstream and downstream of the arm and between pairs of facing suspensions cause disk vibration.

Kubotera *et al*. [9] and Tsuda *et al*. [10] have proven that the presence of a weight-saving hole in a HDD arm creates a larger 3D spiral vortex downstream of the arm and a negative aerodynamic disturbance torque. Gross [11] showed the effect of the thickness of the E-block arm on airflow and subsequently on the FIV on the sliders.

FIV is also affected by other factors determining the interior airflow. Hendriks concluded that the aspect ratio of the disk-to-shroud clearance is a parameter affecting interior HDD airflow [12]. Abrahamson *et al*. [6] reported that decreasing the Ekman number or increasing the axial spacing between disks will reduce vortical structures and allow greater overall mixing.

### B. FIV Mitigation

The mitigation of FIV can be done in many ways. Flow smoothing devices have been introduced into the interior of HDD and their effect on airflow studied and analysed.

Kirpekar *et al*. [7] concluded that inserting a blocking plate between disks (Fig. **3**) was the most effective in reducing FIV, although consuming the highest power. A study by Ikegawa *et al*. in 2006 [13] involved introducing a diverter into the interior of a HDD to divert flow into a bypass channel (Fig. **4**). Resulting airflow velocity near the arm was decreased and the modifications were said to be able to reduce 30% of arm vibration. Zhang *et al*. [14] also discovered that the effects of a flow diverter and vortex splitter can suppress up to 50% of in-plane and out-of-plane vibrations (Figs. **3**, **4**). Results were obtained from LES simulations, and substantiated by calculating the corresponding displacement of the sliders, which was found

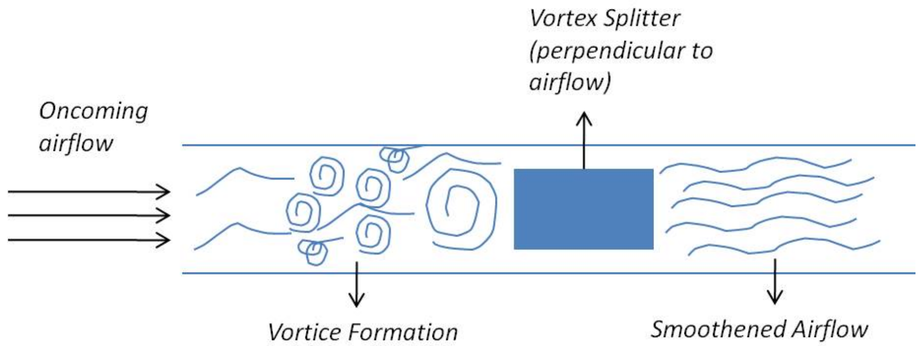


**Fig. (3).** How a vortex splitter works to reduce vortex formation and turbulence.

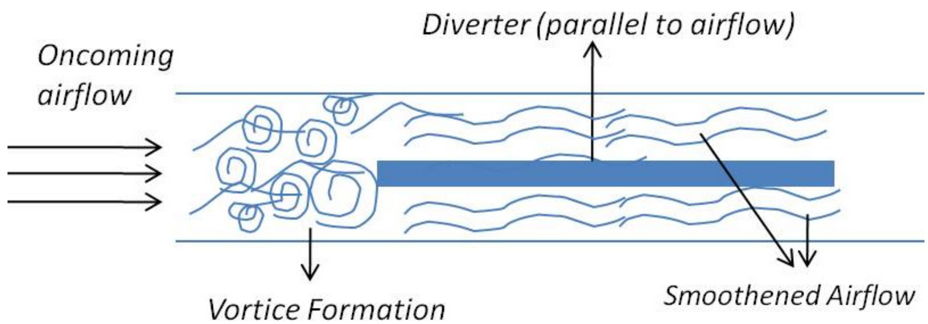


**Fig. (4).** How a flow diverter works to reduce vortex formation and turbulence.

to have decreased with the introduction of the features. However, the geometry and shape of the flow diverters or vortex splitters was not commented on or experimented with.

Other ways to reduce FIV include miniaturizing the HGA [15], and by active suspension such as a piezo-electric dual-stage actuator [16]. The use of disk dampers [17] and the inserting of vibration isolators into HDD cavities [18] are also popular proposed ways of minimizing the effect of FIV. However, while mechanical damping is a highly efficient way to reduce NRRO TMR caused by FIV, the excitation of the vibration itself should be reduced.

### C. Vortex Splitters and Diverters

Vortex splitters and flow diverters are two of the most common FIV mitigation components installed in HDDs to smoothen the internal airflow and reduce turbulence. They are placed in between or above the disks in parallel planes, and act to prevent the formation of vortices and turbulence.

Vortex splitters are small but elongated and are placed perpendicularly across the disks, such that the incoming airflow will come into contact with the splitter length and any vortex formation is prevented. A common position to place vortex splitters is directly downstream of the HDD arm, where the flow field is disrupted and is more turbulent.

Diverters are thin, flat plates aligned circumferentially with the disks. The incoming airflow is diverted into two channels above and below the diverter. Vortex formation is disrupted is prevented along the length of the diverter due to the shortened vertical spacing between the disks. Flow diverters are generally larger in size than vortex splitters, but both work in a similar way to reduce turbulent flow and FIV in HDDs.

### D. Reduce FIV by Filleting

Studies in fluid flow have proven that leading-edge fillets can significantly reduce aerodynamic loss and surface heat transfer and drag [19]. The positive effect of filleting on mechanical components in turbulent fluid flow has been proven by Abu-Hijleh *et al.* [20]. He concluded that fillets provided large reduction in the turbulent kinetic energy. Mahmood *et al.* [21] also investigated the effect of leading edge fillets in a turbomachinery blade passage and it was found that the fillets reduced turbulent intensity as well as heat transfer. However, the application of fillets has been hardly extended to HDD FIV mitigation devices or other interior components, possibly due to the small physical size and complexity in design. This work will incorporate filleting as a way of FIV mitigation.

### E. Selection of Turbulent Models

The Reynolds-averaged Navier-Stokes (RANS) standard $k$-$\varepsilon$ model is one of the most commonly used models to calculate engineering flow. It consists of two separate transport equations for the turbulence kinetic energy ($k$) and its dissipation rate ($\varepsilon$), where the solutions from each equation allow the turbulent velocity and length scales to be determined.

The RNG $k$-$\varepsilon$ model was derived *via* a complex statistical technique and is an improved form of the standard $k$-$\varepsilon$ model. The RNG $k$-$\varepsilon$ model accounts for the effect of swirl on turbulence, and it has an additional term in its $\varepsilon$ equation that makes it more responsive towards rapidly strained and swirling flows. The RNG theory also provides an analytical formula for turbulent Prandtl numbers, while the standard *k-ε* model uses user-specified, constant values. These features justify the use of the RNG *k-ε* model for a wider range of flows including this work.

The LES model, resolves large eddies directly while modelling small eddies. The rationale is:

- Momentum, mass, energy, and transported mainly by large eddies
- Large eddies are more problem-dependent and depend on the geometry and boundary conditions of the flow involved (based on ref. [14])
- Small eddies are less dependent on the geometry, and are more universal and isotropic
- It is more convenient to model large eddies by using a suitable turbulence model

The LES equations are obtained by filtering the time-dependent Navier-Stokes equations in either Fourier (wave-number) or configuration (physical) space to filters out the eddies whose scales are smaller than the filter width or grid spacing used in the computations. The resulting equations govern the dynamics of large eddies. However, in comparison to RANS, LES usually requires finer meshes and a longer flow-time in order to obtain stable statistics of the modelled flow. Hence, LES calculations require much more memory (RAM) and CPU time.

LES requires running a transient solution from an initial condition with a fine grid using an appropriate time step size. The running flow-time needs to be long enough for the solution to become independent of the initial condition and allow the flow statistics to be determined accurately.

Studies have shown that the RANS models (Standard *k-ε* & RNG *k-ε*) are not able to accurately predict highly swirling flow [22], despite the additional modification in the RNG *k-ε* model. The RANS models provides time-averaged pressure and velocity fields and do not distinguish between quasi-periodic large-scale and turbulent chaotic small-scale features of the flow field [23]. The RANS models are unable to accurately reproduce and represent unsteady flow, and there is an inadequate description of unsteady phenomena such as vortex formation and shedding, which occurs in FIV generation.

The LES model applies spatial filtering instead of time averaging, and allows turbulent stresses to be broken down into resolved and modeled stresses for analysis [23]. The main disadvantage of applying the LES models is the high computational costs due to using the extremely fine meshes for the prediction of the vortex structures. Fine time steps are required as well.

In all, LES is generally preferred as it can reveal the dynamic structure of the internal airflow turbulence that RANS would simply smooth out [12]. LES is also able to provide instantaneous information which is much needed for the analysis of transient FIV in HDD. The LES model has been used effectively in a number of studies on FIV [13, 24].

## III. PRELIMINARY STUDIES

### A. Numerical Solvers

Ansys Fluent [25] is used in current study. The three basic standard governing equations are: continuity (1), momentum (2) and energy equations (3) for unsteady compressible fluid and can be written as with usual definitions:

$$\frac{\partial \rho}{\partial t} + \frac{\partial [\rho U_j]}{\partial x_j} = 0 \tag{1}$$

$$\frac{\partial (\rho U_i)}{\partial t} + \frac{\partial [\rho u_i u_j + p\delta_{ij} - \tau_{ji}]}{\partial x_j} = 0 \tag{2}$$

$$\frac{\partial (\rho e_o)}{\partial t} + \frac{\partial [\rho u_j e_{oj} + u_j p + u_i \tau_{ij}]}{\partial x_j} = 0 \tag{3}$$

The finite volume method (FVM) is used in Fluent code. The governing equations are solved over discrete control volumes. FVMs recast the governing partial differential equations in a conservative form, and then discretize the new equation. This guarantees the conservation of fluxes through a particular control volume. The finite volume equation yields governing equations in the form,

$$\frac{\partial}{\partial t} \iiint Q \, dV + \iint F \, d\mathbf{A} = 0, \tag{4}$$

where $Q$ is the vector of conserved variables, $F$ is the vector of fluxes in Navier–Stokes equations, $V$ is the volume of the control volume element, and $A$ is the surface area of the control volume element.

### B. Studies on a Simplified HDD Model

Numerical simulation was used to model the airflow in a simplified HDD model (Figs. **5**, **6**). Firstly, a meshed model of the original HDD was created in meshing software, GAMBIT, based on the given dimensions. Two meshes of different density (127800 *vs* 471900 nodes as tabulated in Table **1**) were created for the same HDD model. Next, the meshes were exported to FLUENT for turbulent flow analysis of the airflow in the disk drive. A disk angular velocity of 500π rad/s was used, giving a Reynolds number of 12.5 x $10^4$, which exceeds the critical Re value of $2\times10^4$ for rotating disk [26]. The standard *k-ε* model in FLUENT was used for numerical simulation of the turbulent HDD airflow for 500 iterations.

Graphical plots of the static pressure and velocity magnitude (Figs. **7**, **8**) along the defined *x* and *z* directions (Fig. **6**) were obtained respectively. The plots from the coarse and fine mesh were largely identical in shape and trend for both quantities. However, the plots from the coarse mesh model were less smooth and contained less plot points than plots from the refined mesh model. It can be concluded that more accurate measures of the specified pressure and velocity properties along the defined sections in the HDD can be obtained by using the Refined Mesh instead of the Coarse Mesh. A further mesh dependent study is conducted until obtain an accepted mesh size, and the subsequent

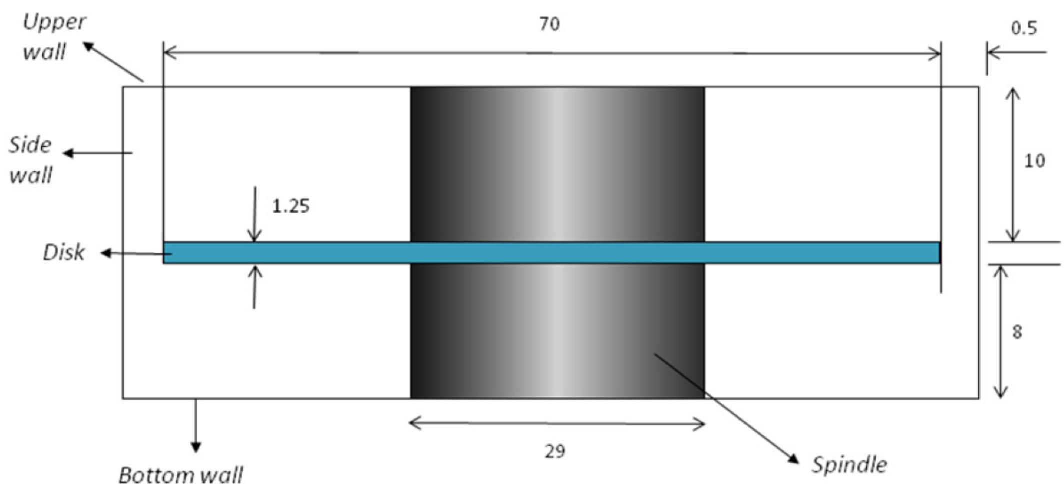


**Fig. (5).** Side view of Simplified HDD Model (dimensions specified are in mm).

meshing size of the models used in the work was similar to the scale of the acceptable mesh used in this preliminary study to minimize error, as well as obtain results in a practical (reasonable) amount of time.

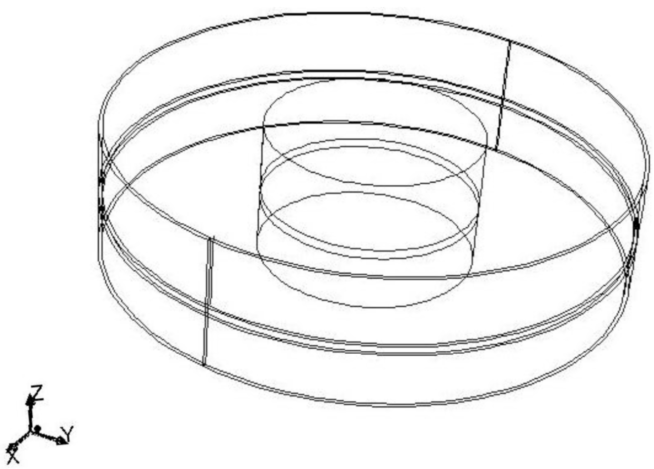


**Fig. (6).** Wireframe of simplified HDD model.

**Table 1. Specifications for Two Different Meshes on the Simplified HDD Model**

| | Coarse Mesh | Refined Mesh |
|---|---|---|
| Mesh Type | Cooper & Map | Cooper & Map |
| Total number of nodes | 127800 | 471900 |
| Total number of hexagonal cells | 112800 | 431200 |
| Minimum volume | $1.70 \times 10^{-3}$ | $1.55 \times 10^{-4}$ |
| Minimum face area | $9.26 \times 10^{-4}$ | $1.56 \times 10^{-4}$ |

### C. Studies on Turbulent Models

This study verified the effectiveness and result of airflow simulation in a HDD using the RANS RNG $k$-$\varepsilon$ model and the LES model in FLUENT. A commercially available full 3.5 inch HDD model was used (Figs. **9**, **10**). A disk angular velocity of $500\pi$ rad/s, giving a Reynolds number of $12.5 \times 10^4$, which exceeds the critical Re value of $2 \times 10^4$ for rotating disk [26]. The RNG $k$-$\varepsilon$ model was run for 10000 iterations. The LES model used was the Sub-Grid Dynamic Smargorinsky-Lilly Model. A time-step of $2 \times 10e^{-6}$s was applied and the model was run for 10000 iterations, with 5 iterations per time-step.

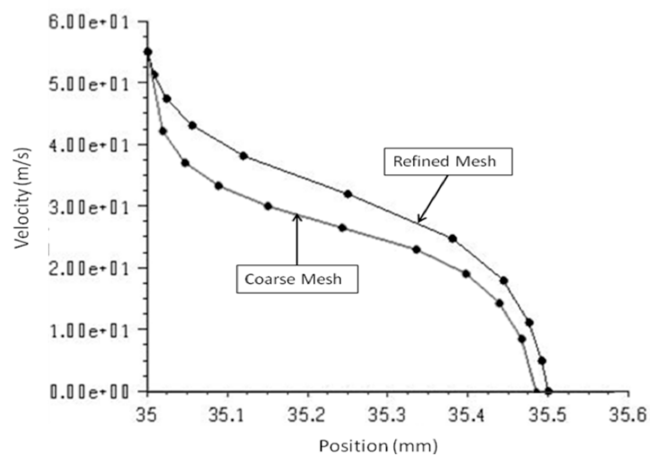


**Fig. (7).** Coarse & Refined Mesh (127800 *vs* 471900 nodes) – Plot of Velocity *vs* Position (x=35mm to 35.5mm).

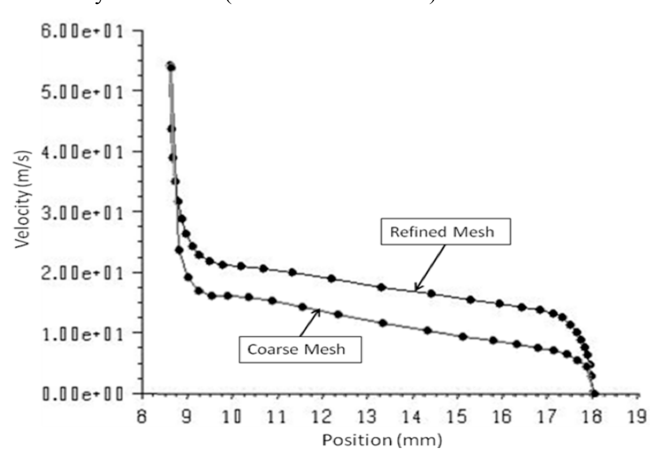


**Fig. (8).** Coarse & Refined Mesh (127800 *vs* 471900 nodes) – Plot of Velocity *vs* Position (z=9mm to 18mm).

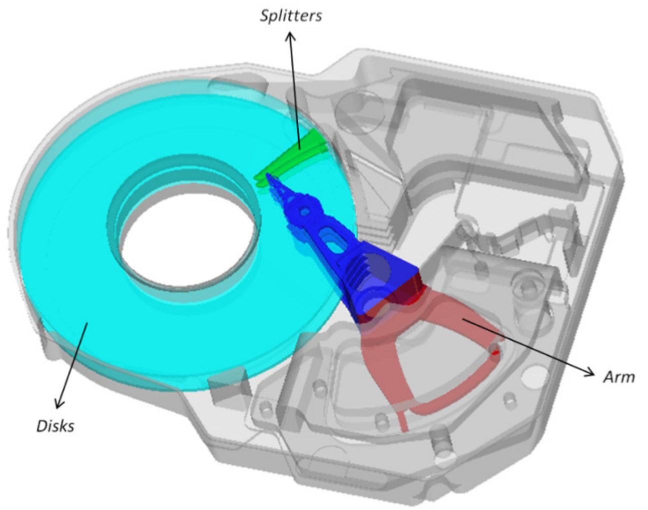


**Fig. (9).** Skeletal view of the 3.5 inch HDD model with top cover removed (model **A** with splitters).

The RNG $k$-$\varepsilon$ model was first used to run a steady state flow simulation for HDD model, and then the converged RNG $k$-$\varepsilon$ model solution was perturbed to produce the initial velocity condition for the start of the LES. Then, the LES Model was run. This method creates a much more realistic initial field for the LES run. It reduces the time needed for the LES to reach a statistically stable mode and decreases the tendency of non-convergence [25].

Figs. (**11**, **12**) show the tangential velocity and static pressure contour plots from the models at the defined horizontal plane of z=9.665mm. Results indicated much more smoothened out flow contours in the RNG $k$-$\varepsilon$ model as compared to the LES model. The numerical values obtained from both models were in the same order and range. The RNG $k$-$\varepsilon$ model gave time-averaged results which did not account for the small perturbations within the flow. The LES model however preserves the forces based on each time step and can give instantaneous information which enables study of transient FIV.

In overall, the unsteady and dynamic internal airflow of the HDD was less accurately represented in the RNG $k$-$\varepsilon$ model as compared to the LES model. However, the RNG $k$-$\varepsilon$ model enabled for the studying of turbulent intensity, which is not enabled with the LES model. The LES model, though, allows for studying of flow perturbations in the z-direction (z-velocity magnitude). Hence, both the RNG $k$-$\varepsilon$ and LES models were selected for used in the subsequent main study. The models would provide results for different quantities in analysis and comparison: Turbulent Intensity would be studied using the RNG $k$-$\varepsilon$ model, while the LES Model would provide results for analyzing Tangential Velocity (m/s), z-Velocity (m/s) and the Total Moment (nm).

## IV. STRUCTURE OPTIMIZATION STUDY OF HDD

Three full 3.5 inch HDD models with different interior configurations were created. Flow simulation using the RNG $k$-$\varepsilon$ and LES Models was then carried out. Similarly, the RNG $k$-$\varepsilon$ model was primarily used before proceeding to run the LES model simulations. The RNG $k$-$\varepsilon$ model was run for 10000 iterations, while the LES model selected was the Sub-Grid Dynamic Smargorinsky-Lilly Model, using a time-step of 2 x $10e^{-6}$s and 10000 iterations, with 5 iterations per time-step.

Model A consists of the full original 3.5 inch HDD with Vortex Splitters (Figs. **9**, **13**), Model B is a full original 3.5 inch HDD with Splitter and Diverters (Figs. **14**, **15**), while Model C is also a full original 3.5 inch HDD consisting the Modified Splitters and Diverters (Figs. **16**, **17**). The hypothesis taken was that Model C would be more effective than Model B in terms of reducing the simulated values such as turbulent intensity and z-Velocity values in HDD airflow. The splitters and diverters in Model C had filleted edges which intend to make them more aerodynamic streamlining towards airflow.

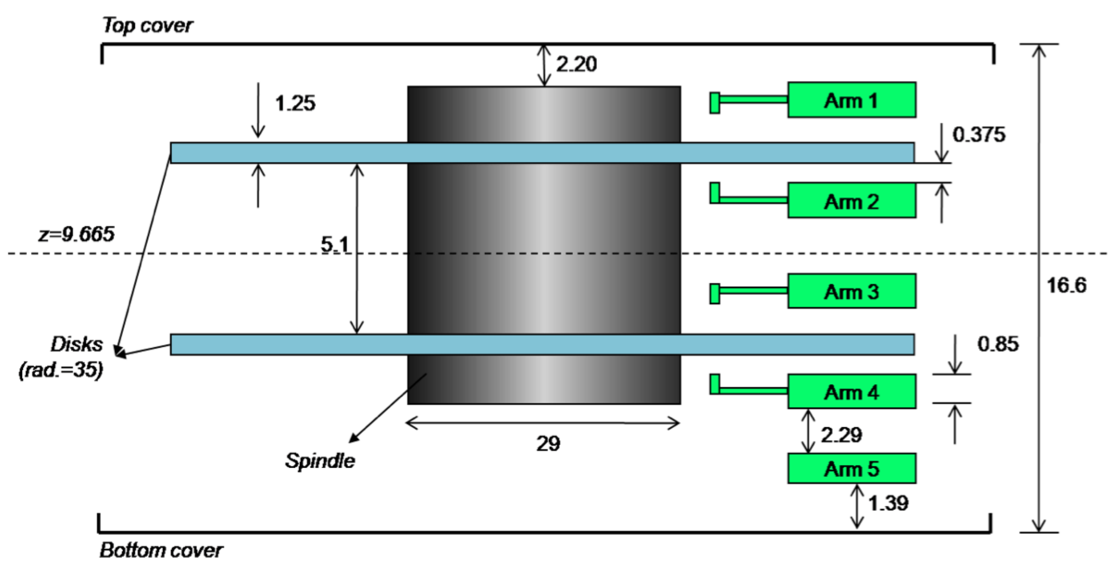


**Fig. (10).** Side view of HDD model used showing z-position of the disks and arms (all in mm).

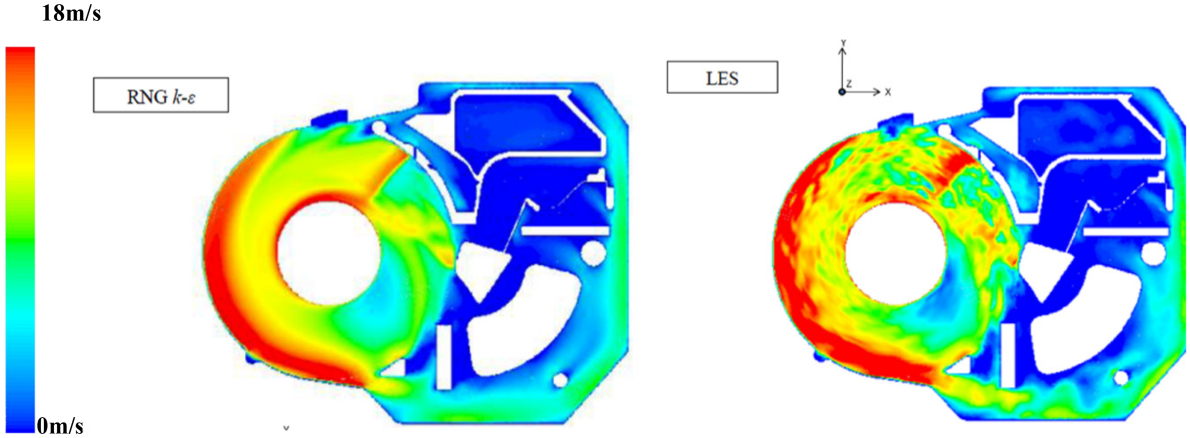


**Fig. (11).** Tangential Velocity contours (in m/s) of the RNG $k$-$\varepsilon$ model (**left**) and LES model (**right**) at z=9.665mm.

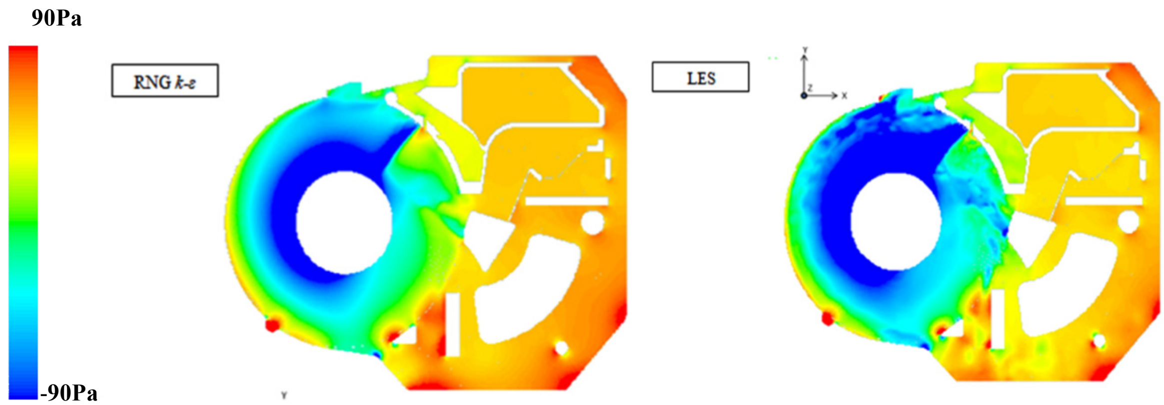


**Fig. (12).** Static Pressure contours (in Pa) of the RNG $k$-$\varepsilon$ model (**left**) and LES model (**right**) at z=9.665mm.

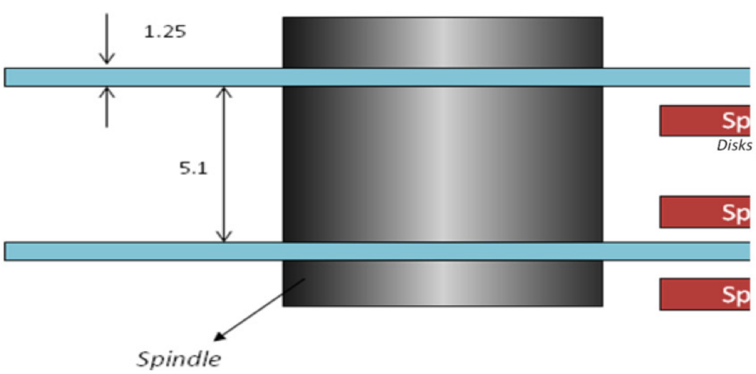


**Fig. (13).** Side view of HDD model **A** showing z-positioning of splitters and disks.

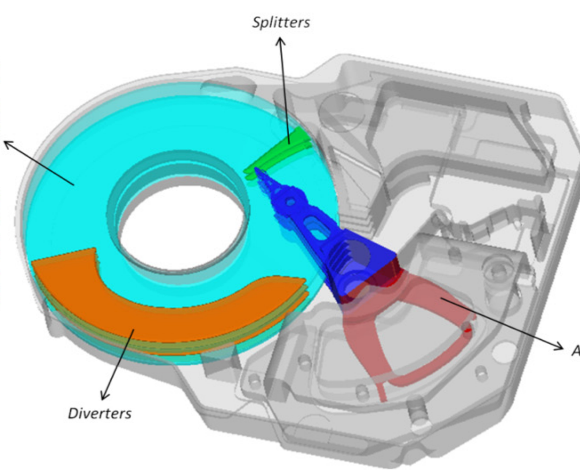


**Fig. (14).** Skeletal view of HDD Model **B** with top cover removed (added with diverters).

### A. Modification and filleting in Model C

Vortex splitters: All the straight edges of the splitters were filleted to remove all sharp contours and created rounder leading edges. The fillet width and angle was identical for all edges. The remaining part of the splitters which was not modified is the part (base root) where it is attached to the HDD.

Flow Diverters: Similarly to the vortex splitters, the straight edges of the flow diverters were filleted to remove all sharp contours and created rounder leading edges. The fillet width and angle was identical for all edges. All diverter edges were filleted.

### B. Results and Discussion

All percentage changes were computed based on taking Model A as base reference. Model B had a 0.17% increase in tangential velocity (m/s) while Model C had a 1.37% decrease (Fig. **18**). Models B and C had substantial reduction in the z-Velocity (m/s) values of 26.2% and 27% respectively. Both models also indicated a decrease in local maximum Turbulent Intensity (%), with a 8.55% decrease for Model B and a 7.11% in Model C (Fig. **19**). Both Models B and C indicated a total increase in about 4% in total

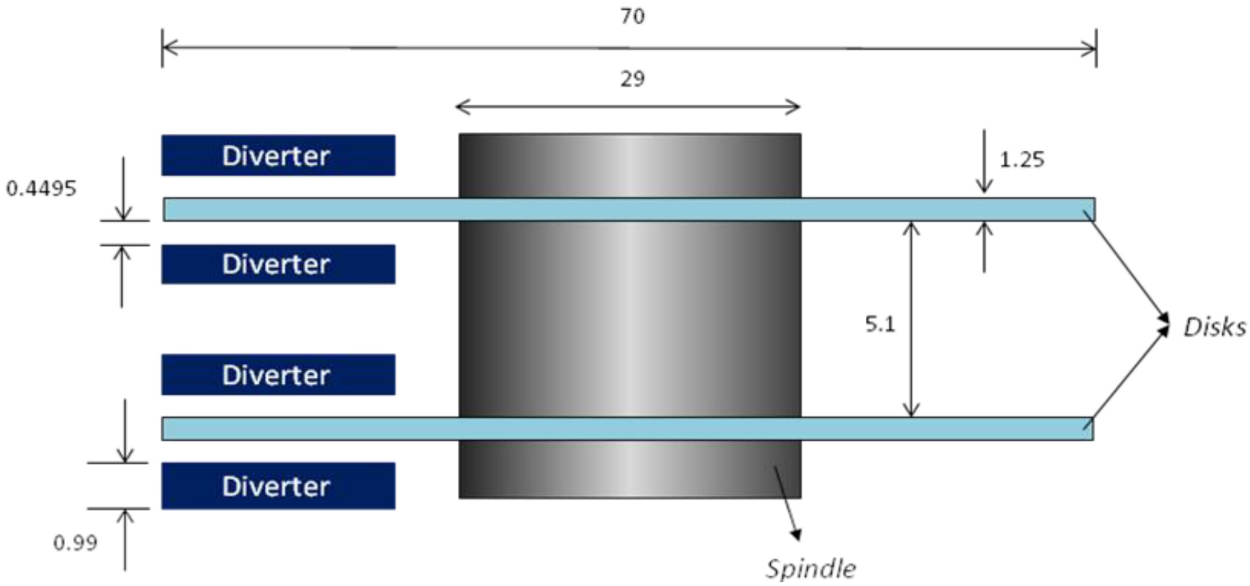


**Fig. (15).** Side view of HDD model **B** showing z-positioning and spacing between diverters and disks.

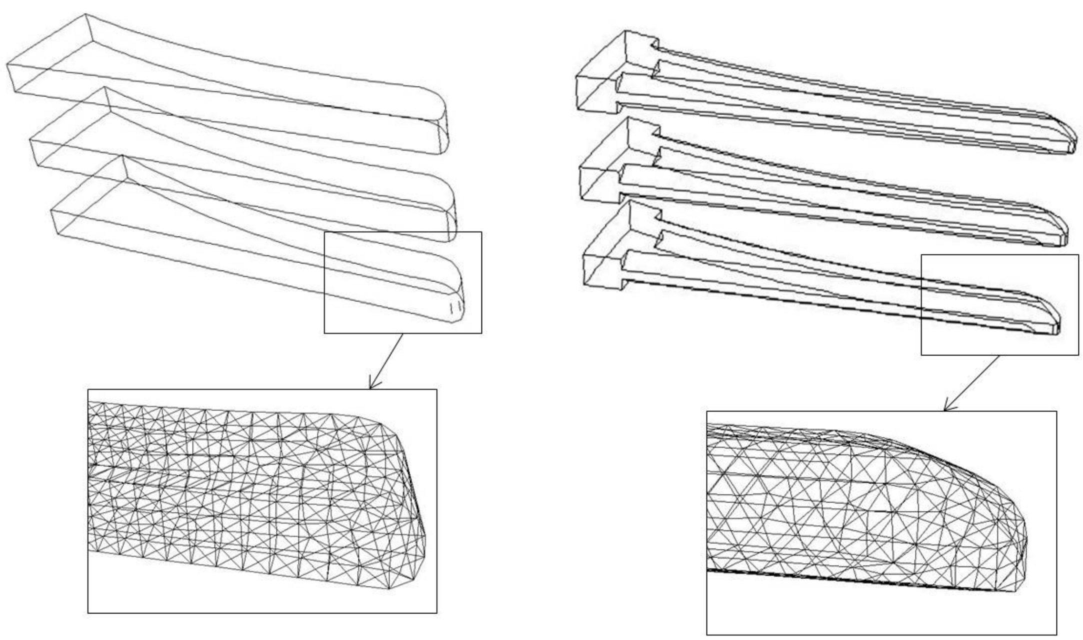

**Fig. (16).** Meshed view of splitter Edge Profile before modification (**left**) and after modification (**right**).

moment, which translates to the total power used to operate the HDD (Table **2**). The indicated increases in power are however still within an acceptable figure in HDD operation (i.e. below 5%).

Analysis of the numerical results shows that the difference in maximum tangential velocity value obtained was negligible, with less than a 5% difference in both Models B and C. The substantial decrease in the z-Velocity values first prove the effectiveness of the introduced diverters in Model B, and a small positive effect of filleting in Model C. The values of turbulent intensity were also reduced by about 7% in each and serve to reinforce the above deductions; however Model C was this time less effective than Model B (when the global maximum turbulent intensity model C was however performed better than B with 72.2% *vs* 66% reduction). The unexpected results of a lower decrease in turbulent intensity in Model C could be accounted for due to the incomplete modification and filleting of the edges of the splitters. The root of the splitters in Model C had consisted of a few remaining sharp edges which left unmodified. These straight edges may have had adverse effects on the internal airflow and overwhelming the effect of filleting the other edges of the splitters and the diverters.

In brief, the diverters are said to have a positive effect on reducing turbulent intensity in HDDs and are therefore recommended. A proposed HDD configuration is to include

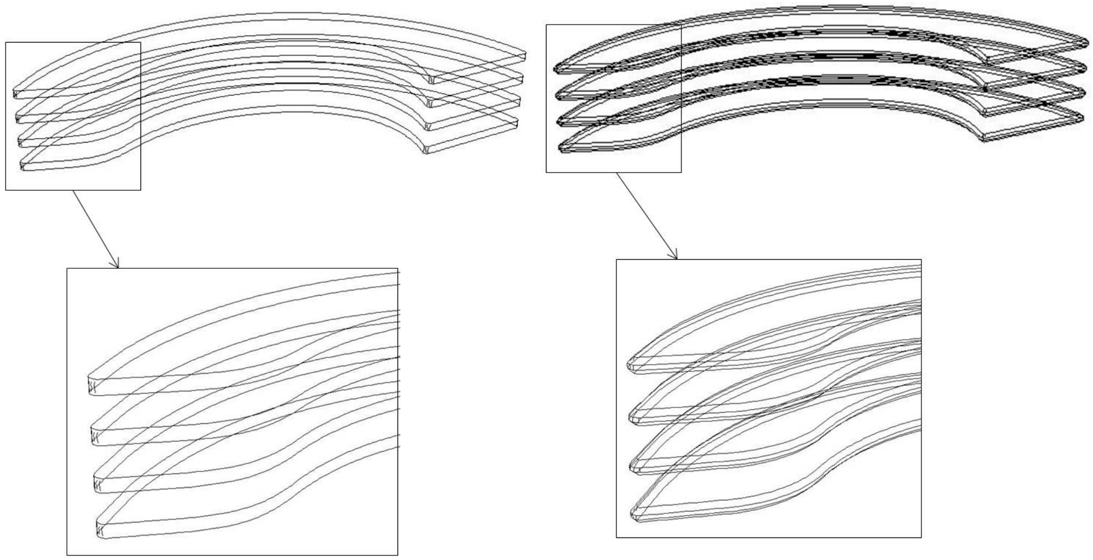

**Fig. (17).** Wireframe view of diverter Edge Profile before modification (**left**) and after modification (**right**).

both vortex splitters and diverters. The filleting of vortex splitters and diverters can be considered, but more experiments should be carried out to more clearly verify the effects of filleting.

## V. CONCLUSION

This paper verified the efficiency of FIV mitigating components namely vortex splitters and flow diverters, including effect in filleting the edges of the components to achieve better aerodynamic towards airflow. Numerical simulations were carried out on HDD models using the RNG $k$-$\varepsilon$ and LES models in FLUENT.

A preliminary study included a flow simulation on a simplified HDD model to benchmark the mesh fineness in obtaining accurate results. We compared two commonly used turbulent models: the RANS RNG $k$-$\varepsilon$ and LES models. Flow simulation was later carried out on a full 3.5 inch commercially available HDD model to justify the choice for the turbulent models to obtain accurate results for analysis.

Flow simulation on three different HDD models encompassed different FIV components and modified geometries was further carried out. The results suggested that the flow splitters and diverters are able to substantially reduce turbulence in airflow. The configuration of filleted splitters and diverters was shown to be less effective in the reduction of turbulent intensity, but further studies should be done to confirm the effectiveness of filleting.

On-going works include modeling of additional geometrical properties of the vortex splitters and diverters, such as shape, size or thickness. Despite the apparent effectiveness of filleting of flow diverters and vortex splitters, it may however prove challenging to manufacture such small filleted components for HDD production. More studies for different disk rotation speeds (i.e. different

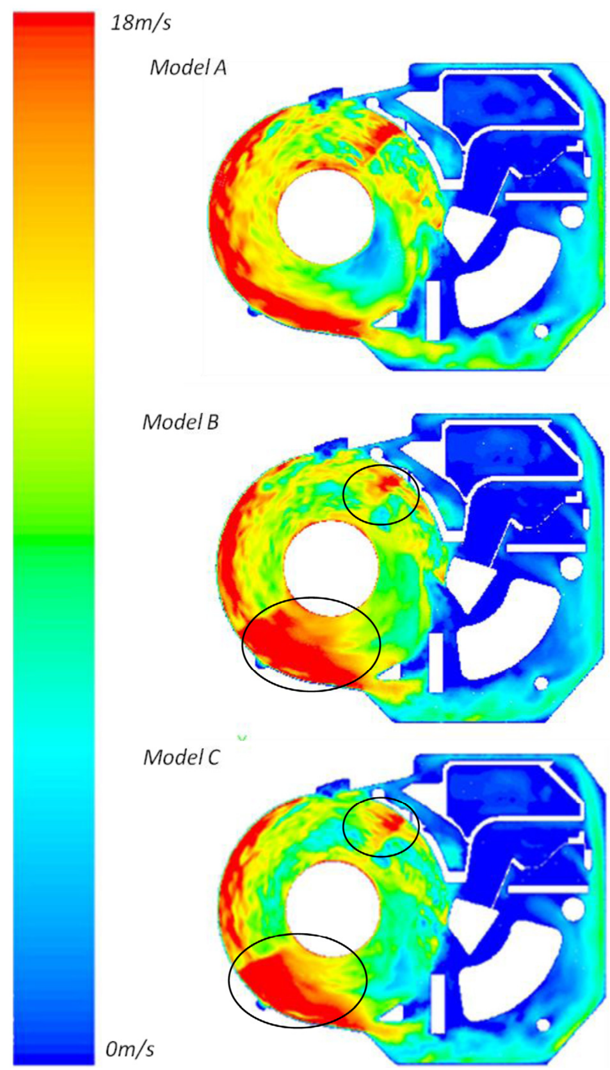


**Fig. (18).** Tangential Velocity contours (in m/s) of Models **A** (top), **B** (middle) and **C** (bottom).

**Table 2. Summary of Percentage Change in values of the HDD models (Taking Model A as Reference)**

| Models/Local Maximum Quantities | Tangential Velocity (m/s) | z-Velocity (m/s) | Turbulent Intensity (%) | Total Moment (Nm) |
|---|---|---|---|---|
| A | | | | |
| B | +0.17% | -26.2% | -8.55% | +4.07% |
| C | -1.37% | -27.0% | -7.11% | +4.21% |

Reynolds number), but maintaining turbulent airflow conditions are needed to establish the relationship of the FIV device effect on airflow and the flow Reynolds number.

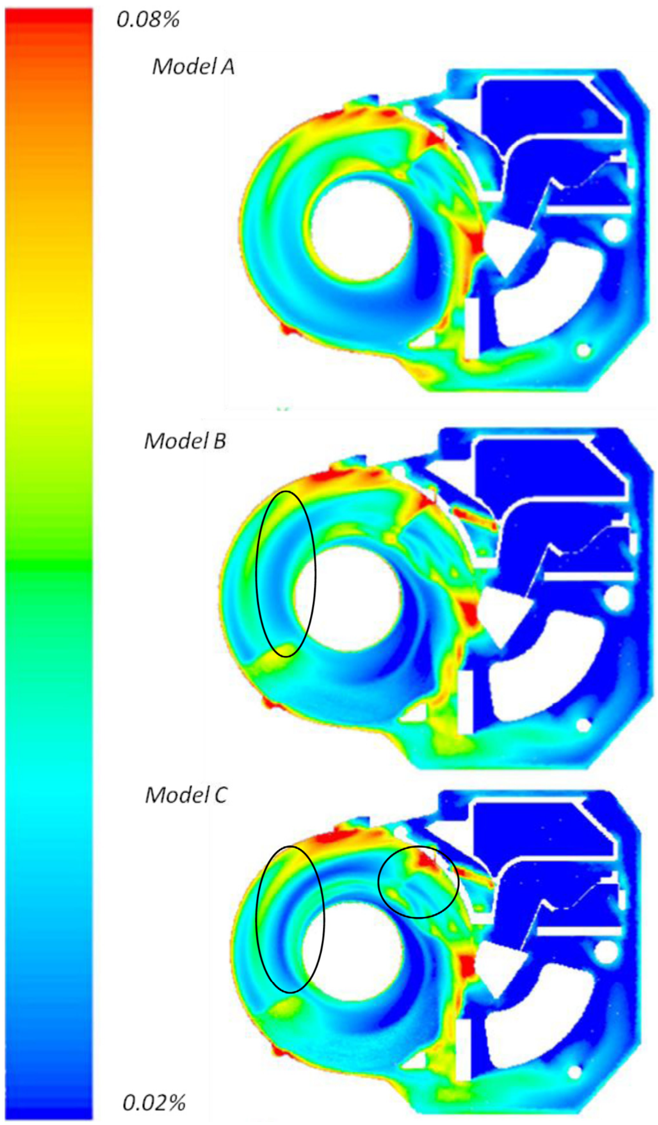


**Fig. (19).** Turbulent intensity contours of Models **A** (top), **B** (middle) and **C** (bottom). Circles indicate area of change from previous model.

## ABOUT THE AUTHOR

**Eddie Ng** received Ph.D at Cambridge University with a Cambridge Commonwealth Scholarship. His main area of research is thermal imaging, biomedical engineering; CFD/CHT. He is a faculty at the Nanyang Technological University in the School of Mechanical and Aerospace Engineering. He has published more than 255 papers in SCI journals (168); SCI conference proceedings (25), textbook chapters (50) and others. Eddie is Editor-in-Chief for the J. of Mechanics in Medicine and Biology and J. Med. Imaging and Health Informatics; Assoc. Editor for Int. J. of Rotating Machinery; Computational Fluid Dynamics J. (CFDJ); Int. J. of Breast Cancer, Chinese J. of Medicine, Open Medical Informatics J., Open Numerical Methods J., J. of Healthcare Engineering and strategy Assoc. Editor-in-Chief for World J. of Clinical Oncology. Ng is an invited speaker for many int. scientific confs/workshops. Recently, he has co-edited 7 books on “Cardiac Pumping and Perfusion Engineering” by WSPC Press (2007); “Imaging and Modelling of Human Eye” by Artech House (2008); “Distributed Diagnosis and Home Healthcare” Vols. 1 & 3, by ASP (2009 & 2011); “Performance Evaluation in Breast Imaging, Tumor Detection & Analysis” by ASP (2010); “Computational Analysis of Human eye with Applications” by WSPC (2011) and “Multi-modality state-of-the-art: Human eye imaging and modeling” by CRC (2011). Also, he co-authored a text book: “Compressor Instability with Integral Methods” by Springer (2007). More details are available upon request and in URL: http://www.researcherid.com/rid/A-1375-2011.

## REFERENCES

[1] Kim B, Raman A, Mote CD. Prediction of aeroelastic flutter in a hard disk drive. J Sound Vib 2000; 238(2): 309-25.

[2] Frank P, Wood R. A perspective on the future of hard disk drive technology, IEEE Asia-Pacific Magnetic Recording Conference; Singapore 2006; pp. 1-2.

[3] Shimizu H, Tokuyama M, Imai S, Nakamura S, Sakai K. Study of aerodynamic characteristics in hard disk drives by numerical simulation. IEEE Trans Magn 2001; 37(2): 831-36.

[4] Chan AS. Minimizing flow induced vibration in a hard disk drive with a hybrid planar plate having a bypass channel. US Patent App. 20,090/268 2008; 341.

[5] Lee DY, Hwang J, Bae GN. Effect of disk rotational speed on contamination particles generated in a hard disk drive. Microsyst Technol 2004; 10(2): 103-8.

[6] Abrahamson SD, Eaton JK, Koga DJ. The flow between shrouded corotating disks. Phys Fluids A 1989; 1: 241-51.

[7] Kirpekar S, Bogy DB. A study on the efficacy of flow mitigation devices in hard disk drives. IEEE Trans Magn 2006; 42(6): 1716-29.

[8] Shimizu H, Shimizu T, Tokuyama M, Masuda H, Nakamura S. Numerical simulation of positioning error caused by air-flow-induced vibration of head gimbals assembly in hard disk drive. IEEE Trans Magn 2003; 39(2): 806-11.

[9] Kubotera H, Tsuda N, Tatewaki M, Maruyama T. Aerodynamic vibration mechanism of HDD arms predicted by unsteady numerical simulations. IEEE Trans Magn 2002; 38(5): 2201-03.

[10] Tsuda N, Kubotera H, Tatewaki M, Noda S, Hashiguchi M, Maruyama T. Unsteady analysis and experimental verification of the aerodynamic vibration mechanism of HDD arms. IEEE Trans Magn 2003; 39(2): 819-25.

[11] Gross HM. Off-track vibrations of the read-write heads in hard disk drives. Ph.D. dissertation. Berkeley, USA: Uni. of California 2003.

[12] Hendriks F. On Taylor vortices and Ekman layers in flow-induced vibration of hard disk drives. Microsyst Technol 2010; 16(1): 93-101.

[13] Ikegawa M, Hirono Y, Mukai H, Kaiho M. Decreasing airflow velocity in hard disk drives with a spoiler and bypass. IEEE Trans Magn 2006; 42(10): 2594-6.

[14] Zhang QD, Tan CS, Sundaravadivelu K, *et al*. Mitigation of flow induced vibration of head gimbal assembly. Microsyst Technol 2010; 16(1): 213-9.

[15] Nakamura S, Wakatsuki K, Takahashi H, Saegusa S, Hirono Y. Flow-induced vibration of head gimbal assembly. IEEE Trans Magn 2004; 40(4): 3198-200.

[16] Teerhuis AP, Cools SJM, de Callafon RA. Reduction of flow-induced suspension vibrations in a hard disk drive by dual-stage suspension control. IEEE Trans Magn 2003; 39(5): 2237-9.

[17] Yoo Y, Lee J, Kang S. Disk damper and hard disk drive having the same. US Patent App. 20,070/097 2006; 545.

[18] Colligan TR. Hard disk drive with vibration isolators located at mounting points. US Patent App 20,090/097 2007; 195.

[19] Shih TIP, Lin YL. Controlling secondary-flow structure by leading-edge airfoil fillet and inlet swirl to reduce aerodynamic loss and surface heat transfer. J Turbomachinery 2003; 125: 48-56.

[20] Abu-Hijleh B, Tu J, Subic A. Effect of a rotor's aspect ratio and casing inlet/outlet geometry on the efficiency of a rotor-casing assembly. Int J Veh Des 2006; 40(4): 349-70.

[21] Mahmood G, Gustafson R, Acharya S. Experimental investigation of flow structure and Nusselt number in a low-speed linear blade passage with and without leading-edge fillets. J Heat Transfer 2005; 127: 499.

[22] Pope SB, Pope S. Turbulent flows. Cambridge, UK: Cambridge University Press 2000,.

[23] Breuer M, Jovičić N, Mazaev K. Comparison of DES, RANS and LES for the separated flow around a flat plate at high incidence. Int J Numer Methods Fluids 2003; 41(4): 357-88.

[24] Kazemi M, Tokuda A. An investigation on flow-induced offtrack vibration of head gimbal assembles in hard disk drives. ASME Information Storage and Processing Systems Conference; Santa Clara, CA, USA 2007; pp. 1-3.

[25] ANSYS FLUENT 6.3 User's Guide. Chapter 12. Modelling Turbulence, 2011.

[26] Aruga K, Suwa M, Shimizu K, Watanabe T. A study on positioning error caused by flow induced vibration using helium-filled hard disk drives. IEEE Trans Magn 2007; 43(9): 3750-55.


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